Ventilative Cooling in Energy Renovated Single-Family Houses in Temperate Climates

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BY
THEOFANIS PSOMAS

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AALBORG UNIVERSITY
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Natural ventilation and passive cooling methods

Thermal comfort

Energy efficient and sustainable buildings

ENGLISH SUMMARY

For occupants of energy renovated single-family houses in European temperate climates overheating risk is a new challenge that they have never experienced before now. Building users do not have the technical knowledge of how to efficiently eliminate the risk and their attitude and behavior push the problem in the opposite direction.

This thesis contains numerical analysis of four reference dwellings, in representative climatic conditions of Northern and Central Europe. Concerning targeting of the efficiency improvement of the building elements, the major and deep energy renovation measures in dwellings in temperate climates (to decrease the energy use for heating) increase the average and maximum indoor temperatures in room and building level and the overheating risk and overheating period for the occupants. In terms of overheating, the alarming energy renovation measures among the examined cases are the thermal insulation of the floor and the increase of the airtightness of the dwelling. Positive contribution offers the decrease of the g-value of the windows. The most effective renovation measure, among the examined ones is the installation of the mechanical ventilation system and the application of high air change rates. As part of the renovation measures, mainly external shading systems applied with simple control strategies may diminish the overheating effectively, especially to the Northern temperate climatic conditions.

Supplementary numerical analysis of two out of four reference dwellings under different renovation scenarios shows that the ventilative cooling method and control strategies through opening systems may be a very energy-effective, attractive, and sustainable solution for diminishing overheating risk only if systems are automated controlled. Indoor air quality based, manual control of the opening systems (and mechanical ventilation systems) cannot assure environmental conditions without major overheating incidents. In colder temperate climatic conditions (Nordic countries), automated window opening control systems based on indoor natural ventilation cooling set points and monitoring of the outdoor conditions with integrated simple heuristic ventilative cooling algorithms may significantly diminish the overheating risk. In the hotter temperate climatic conditions (Central Europe), these systems may not be sufficient to eliminate the risk alone, but in combination with other passive cooling methods.

In addition, this research study presents, in detail, a new developed automated window opening control system and highlights its ability to improve the indoor environment during the cooling season. The indoor thermal and air quality assessment of a deep energy renovated single-family house in Denmark illustrates the fact that mechanical and passive ventilation components and shading systems, if manually controlled, cannot assure indoor environmental conditions without major violations (summer

2015). In contrast, the use of the developed window system may significantly diminish the indoor thermal discomfort, assessed by static and dynamic metrics, in all rooms without any significant compromise of the air quality (summer 2016). The low energy use of the developed window systems as well as the total energy savings, more than 95%, from the deactivation of the mechanical ventilation system add extra to the performance value of the system itself. The simulation of the developed window system (ventilative cooling function), on coupled building performance simulation environments, is possible under the proposed framework. Under this framework, the simulation of any other developed window system or more sophisticated ventilative cooling control strategy is possible.

Finally, the comparison and statistical analysis on the overheating metrics of this research study indicates that it is not possible to develop a general relationship between both dynamic metrics and all the examined static metrics. On the other hand, analysis indicates that it is possible to develop linear relationships between static indices for general use, independently of the building and climate. Finally, dynamic indices originate from the same adaptive theory highly correlated with each other.

DANSK RESUME

For brugere af energi-renoverede enfamiliehuse i europæisk tempereret klima er overophedningsrisikoen en ny udfordring, som de ikke har oplevet før nu. Brugere af huse har ikke den tekniske viden til hvordan man effektivt eliminere risikoen, og deres holdninger og opførsel skubber problem i den anden retning.

Denne afhandling indeholder numerisk analyse af fire referenceboliger i repræsentative klimaforhold i det nordlige og centrale Europa. Vedrørende speciel fokus på de effektive forbedringer i bygningselementer øger de større energirenovationstiltag i boliger i tempereret klima (for at mindske energiforbruget ved opvarmning) den gennemsnitlige og maksimale indendørstemperatur i rum- og bygningsniveau og overophedningsrisikoen og overophedningsperioden for brugerne. Med hensyn til overophedning er de alarmerende energirenoveringstiltag blandt de undersøgte sager den termiske isolering af gulvet og forøgelsen af lufttætheden i boligen. Det positive bidrag tilbyder en mindskning af g-værdien ved vinduerne. Det mest effektive renoveringstiltag blandt de undersøgte tiltag er installation af mekanisk ventilationssystem og tilføjelsen af høje rater for luftskifte. Som en del af renoveringstiltagene vil hovedsageligt eksternt afskærmningssystemer anvendt med simple kontrolstrategier måske effektivt mindske overophedningen, specielt i nordligt tempereret klimaforhold.

Yderligere numerisk analyse af to af de fire referenceboliger under forskellige renoveringsscenarier viser, at den ventilative afkølingsmetode og kontrolstartegier via åbne systemer kan måske være en meget energieffektiv, tiltalende og bæredygtig løsning for at mindske overophedningsrisikoen, kun hvis systemerne styres automatisk. Indendørs luftkvalitetsbaseret manuel kontrol af åbningssystemer (og mekaniske ventilationssystemer) kan ikke garantere miljømæssige forhold uden store tilfælde af overophedning. I køligere klimaforhold (nordiske lande) vil automatiske kontrolsystemer for åbning af vinduer, baseret på indstillingsværdier for afkøling ved indendørs naturlig ventilation og kontrol af udendørsforhold med integrerede simple heuristiske ventilative afkølingsalgoritmer, måske betragteligt mindske overophedningsrisikoen. I varmere tempereret klimaforhold (central Europa), vil disse systemer måske ikke være tilstrækkelige nok til alene at eliminere risikoen, men i kombination med andre passive afkølingsmetoder.

Derudover præsenterer denne forskningsundersøgelse i detaljer et nyt udviklet automatisk vinduesåbning kontrolsystem og fremhæver dettes evne til at forbedre indendørsmiljøet i afkølingssæsonen. Vurderingen af den indendørs termiske- og luftkvalitet af en dybt energirenoveret enfamiliehus i Danmark illustrerer det faktum, at mekaniske og passive ventilationskomponenter og afskærmningssystemer, hvis disse er manuelt styret, kan ikke garantere indendørs miljøforhold uden større overtrædelser (sommer 2015). Modsat kan brugen af det udviklede vinduessystem

betragteligt mindske indendørs termiske gener, vurderet af statiske og dynamiske metrikker, i alle rum uden noget mærkbart kompromis af luftkvaliteten (sommer 2016). Det lave energiforbrug ved de udviklede vinduessystemer såvel som de totale energibesparelser, mere end 95%, fra deaktivering af det mekaniske ventilationssystem tilføjer mere til egenskaberne af systemet. Simulering af det udviklede vinduessystem (ventilativ afkølingsfunktion) på samvirkende simulationsmiljøer for bygningspræstationer, er mulig under den foreslåede struktur. Ved denne struktur er simulering af ethvert andet udviklet vinduessystem eller mere sofistikeret ventilativ afkølingskontrolstrategi mulig.

Endeligt, sammenligning og statistisk analyse af overophedningsmetrik i denne forskningsundersøgelse indikerer, det ikke er muligt at udvikle et generelt forhold mellem både dynamisk metrikker og alle undersøgte statiske metrikker. På den anden side indikerer analysen, at det er muligt at udvikle lineære forhold mellem statiske indekser til generel brug, uafhængigt af bygningen og klimaet. Endeligt, dynamiske indekser der stammer fra samme adaptive teori hænger godt sammen med hinanden.

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This work is dedicated to my father, Charalampos Th. Psomas.

Theofanis Psomas

Aalborg, 2017

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NOMENCLATURE-ABBREVIATIONS

C_d: Discharge coefficient

C_p: Wind pressure coefficient

T_{ed-i}: Daily mean external air temperature, i-th previous day [^oC]

T_{max}: Maximum yearly indoor operative temperature [^oC]

$T_{nv.setpoint}$: Indoor natural ventilation cooling set point [^oC]

$T_{o,max/min}$: Limit value of indoor operative temperature (adaptive comfort theory) [^oC]

T_{rm}: Running mean outdoor temperature [^oC]

$u_c(k)$: Opening percentage, step k [%]

$u_d(k)$: Disturbance state, step k [^oC]

$x(k)$: Measured state, step k [^oC]

Ach: Air change rate per hour

AFN: Airflow network

A.H.: Absolute humidity [g/m^3]

AUS: Austrian case study (A)

BAS: Building automation system

BCVTB: Building controls virtual test bed

BR15: Danish building regulations

BPS: Building performance simulation

CCP: Climatic cooling potential

CIBSE: Chartered Institution of Building Services Engineers (U.K.)

CO_2: Carbon dioxide [ppm]

CTF: Conduction transfer function

DHRS: Degree-hours outside the range index [ºCh]

DK: Danish case study (D)

DR: Daughter's room

DT: Difference between peak indoor and annual average outdoor temperature [ºC]

EU-28: European Union, 28 members

F_temperature: Exceedance index, temperature [%]

FR: South French case study (F)

GDP: Gross domestic product

IAQ: Indoor air quality

ISO: International Organization for Standardization

LAN: Local area network

MB: Main bedroom

Met: Metabolic equivalent of task (unit)

MV: Mechanical ventilation

nZEB: Nearly zero energy building (renovation scenario)

PMV: Predicted mean vote

POR: Percentage outside the range index [%]

ppm: Parts per million (unit)

R^2: Adjusted coefficient of determination

RBC: Rule-based control

R.H.: Relative humidity [%]

SR: Son's room

TABULA: Typology approach for building stock energy assessment project

U: British case study (U.K.)

U-value: Thermal transmittance [W/m^{2}K]

U.K.: United Kingdom

CHAPTER 1. INTRODUCTION

1.1. BACKGROUND

In December 2015, European Union (EU-28) members set out high climate mitigation and energy targets as part of the Paris agreement (1). The European building sector is one of the largest untapped sources of cost-effective energy savings with high carbon dioxide (CO_2) decreasing potential, and it will play a significant role in achieving these strategic targets (2). The building stock is the largest single energy user in Europe (3). In 2012, the total final energy use was up to 40% and the total carbon dioxide emissions up to 38% (3). Approximately 25 billion m^2 (2011) of floor space is in use in the EU-28, Switzerland and Norway (4). Residential buildings are the 75% of the total building stock, and single-family houses are 64% of this part (4). More than 35% of the residential buildings have been constructed before the 1960s, without or with the first energy regulations (4). Approximately 150 million buildings are not energy efficient, and 80% of them will be in use in 2050 as well (5).

Energy efficiency policies have diminished the final energy use of the residential building sector by approximately 2.5% since 2007 (3). Directive 31/EU adopted in 2010 promoted the decrease of energy use in buildings, thereby highlighting a range of environmental, financial, health, social and energy security benefits (6). In addition, European regulation urges member states to introduce cost-optimal requirements for renovation projects, as well as, to eradicate the market barriers and to activate the necessary financial tools for the faster convergence (2012; 7). Energy efficiency Directive 27/EU adopted in 2012 forwarded requirements for member states to develop and apply long-term investment strategies for the renovation of the building stock on national level (8). The building sector was accounted for approximately 7% of the European GDP and for 8.8% of total non-financial business economy employment (2011; 3). The energy renovation market in Europe has an estimated turnover of more than €100 billion per year, which equals to more than 800,000 jobs in 2015 (1). These numbers are expected to be increased by almost 50%, with the adoption of stricter energy saving targets (1).

Fuel and energy poverty is an existing problem in the EU, especially in member states with per capita GDPs below the average (3). In 2012, 11% and 19% of the citizens were unable to keep their dwellings comfortable in winter and summer respectively (3). Renovation strategies are related highly with fuel and energy poverty. Improvement of the energy efficiency of the building stock is apparently the best way to diminish energy use and carbon emissions, to fight fuel poverty and climate change, and to improve competitiveness and employment in Europe (3, 9). The current renovation rate is low (approximately 1.2%) mainly because of the economic recession of 2007 and afterwards (2, 9). More and deeper renovation projects are expected in the next decades if the full technical and financial potential are to be realized (2, 9).

In 2012, Denmark had more than 1.5 million heated residential buildings in use, which equals to approximately 300 million m^2 (10). Almost 80% of them are single-family dwellings (10). More than 80% of the stock of the dwellings were built before 1980 and before building regulations contained efficiency energy requirements for buildings (11). In spite of the tightening of the building energy regulations from the end-1970s and onward, the existing detached houses offer a colossal potential for energy conservation and savings (key area for investments; 11). In 2014, Danish authorities presented a strategy for energy renovation of buildings, targeting to diminish the carbon emissions and energy use without compromising environmental, social, and comfort quality (11).

The recently applied new Danish building regulations (BR15) set strict compliance requirements for residential buildings under energy renovation and suggest cost-effective measures targeting mainly the heating season (12). The suggested solutions, and measures are oriented mainly to the increase of the envelope airtightness and insulation levels in building elements (12, 13). The strong interest to the extended and intense Northern European cold conditions drive the stakeholders, designers, building developers, and researchers to pay inadequate attention to the thermal environment of the residential buildings during the hotter months (9, 12). The use of simplified monthly methods, suggested by the regulations and guidelines, is based on past and anachronistic experiences and rules of thump, averaging and underestimating the overheating risk in both time and space (9, 12).

A number of research projects have verified and emerged overheating risk during the design and operation phases in nearly zero energy or existing residential buildings under major or deep renovation without mechanical cooling systems in temperate climates (14-17). Post-occupancy surveys and long lasting comfort studies have also documented and monitored high indoor temperatures over 27ºC and 28ºC even in Scandinavian countries (18, 19). The decrease of the infiltration rates, the increase of the ambient temperatures by climate change and heat island effects and the large south-oriented façades result in extended and intense thermal discomfort and overheating incidents during cooling periods (9, 14-19). Highly efficient residential buildings are also more sensitive to variation of the environmental conditions than older dwellings (14-19).

For occupants of these climatic conditions, overheating risk is a new challenge that they have never experienced before now (9). Occupants do not have the technical knowledge of how to efficiently eliminate the risk and their behaviors push the problem in the opposite direction (9, 18, 20, 21). Health evidences show that high indoor temperatures for extended periods significantly degrade the indoor environmental quality, affect the productivity, satisfaction, well-being, and morale of the inhabitants and increase the morbidity and vulnerability of them (22, 23). Ventilative cooling can be an energy-efficient, attractive, sustainable, and low-cost solution to avoid overheating incidents and to diminish cooling loads in energy renovated houses in temperate climates.

1.2. LITERATURE REVIEW

This section presents a detailed literature review regarding two major subjects: overheating definitions and thermal comfort assessment metrics and ventilative cooling performance, effectiveness, potentials, and limitations within building design. The analysis aims at examining, investigating, and presenting the state-of-the-art research work on the aforementioned topics in order to highlight non-defined or purely clarified scientific areas for further examination and analysis.

1.2.1. OVERHEATING AND THERMAL DISCOMFORT ASSESSMENT

International Standard ISO 7730:2005 defines thermal comfort as *"that condition of mind which expresses satisfaction with the thermal environment"* (24). The Standard defines analytically the optimum indoor thermal conditions (energy balance model) acceptable to the majority of occupants (24). For this definition, the Standard promotes the concept of PMV (predicted mean vote; 24). The developed concept is applied to totally controlled indoor environments where occupants have no interaction or direct access to outdoor conditions, like fully air-conditioned spaces (25). The concept is not applicable to indoor spaces of "free-running or free-floating" naturally ventilated buildings where natural ventilation systems allow outdoor conditions to affect the internal spaces (25). In addition, occupants have a high degree of control over their own environment (windows, shadings, fans, and others; 25). For this type of buildings, the concept of the adaptive thermal comfort was developed (25). Users of these spaces are more tolerant to temperature fluctuations based on outdoor conditions (25). This concept is also applicable to residential buildings (sedentary physical activities with metabolic rates ranging from 1.0 to 1.3 met) without active cooling systems where occupants make additional adjustments (adaptation) to their clothing, activity, and posture (25, 26, 27). Table 1-1 presents the recommended ranges of indoor operative temperatures as function of the running mean outdoor temperature for different Categories (graded I to IV) and European Standards (equation 1-1 and 1-2; 25, 28). This concept is applicable to the summer season and transition months. Spaces with mechanical ventilation systems with unconditioned air and operable natural ventilation systems may be assessed by the dynamic adaptive theory (28). At the new European Standard, there is a correction of the lower limit (1°C) of the concept and an extension of the applicability range for the running mean outdoor temperature (from 15-30°C to 10-30°C; 28). Different equations of the adaptive concept have been developed and proposed over time (29). The differences are related mainly to the calculation period, the regression model, and the ambient temperature applicability range (30).

$$T_{rm} = \frac{T_{ed-1} + 0.8 * T_{ed-2} + 0.6 * T_{ed-3} + 0.5 * T_{ed-4} + 0.4 * T_{ed-5} + 0.3 * T_{ed-6} + 0.2 * T_{ed-7}}{3.8}$$

(equation 1-1)

$T_{o,max/min} = 0.33 * T_{rm} + 18.8 \pm category\ limit$ (equation 1-2)

$T_{o,max/min}$=limit value of indoor operative temperature, ^oC

T_{rm}=running mean outdoor temperature, ^oC

T_{ed-i}=daily mean external temperature for the *i-th* previous day, ^oC

Table 1-1: Description of the applicability and limits (equations 1-1 and 1-2) of the Categories (I to IV) for two European Standards (25, 28).*

Category	**Explanation**	**Limits**
I	*"High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons."*	±2 +2 and -3*
II	*"Normal level of expectation and should be used for new buildings and renovations."*	±3 +3 and -4*
III	*"An acceptable, moderate level of expectation and may be used for existing buildings."*	±4 +4 and -5*
IV	*"Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year."*	Below and above other Categories.

In engineering and building sciences there is no precise, rigorous or widely accepted definition of what constitutes overheating and overheating risk in general (22, 29, 31). Overheating is the result of internal (occupants, appliances, domestic hot water systems) and/or external (solar gains, gains through the fabric, urban micro-environment) heat build-up indoors (32). The majority of the definitions are epidemiological, physiological, productivity or thermal comfort related (22, 29, 31). Residential buildings should offer a safe and healthy environment to a spectrum of occupants from infants to vulnerable people (elderly, obese, and others; Table 1-1). The effects of overheating in buildings range from discomfort and reduced performance to tremendous health problems and mortality (22, 33). Prolonged exposure, especially during night time, drastically affects the occupants' well-being and satisfaction (22, 33). Increased sleep fragmentation and awakening are linked to low quality of life and decreased performance, mental concentration and productivity (22, 33). Occupants respond differently to increased temperatures based on physiological (anatomical), behavioral, social, and cultural reasons (22, 33). Sweating is the most well-known and anodyne reaction of the thermoregulation mechanism to high temperatures. Mild heat related health effects are dehydration, heat cramps, rash, edemas, and fainting (33). Heat strokes, and exhaustion belong to severe heat illnesses and affect not only the occupants with chronic diseases, respiratory illnesses, and social isolation but also young health people (33). Heat events during the beginning of the cooling period present higher risk (33).

For more than a century, literature has developed over 160 different climatic stress indices (34). Approximately seventy indices were used for overheating risk assessment (35). Metrics that assess the indoor space for a specific time and for a specific user (perception) are not able to assess the thermal quality of the building in total (28, 29, 31, 35). The European comfort Standard has proposed a new category of metrics to cover this analysis (28). Long-term indices cumulate in one numerical value - the thermal discomfort of a building over a longer period - taking into consideration all spaces (weighting average in net volume term; 25, 29, 31, 35). The dwelling meets the criterion for a specific category if the rooms representing 95% of building volume (or area) meet this criterion (25). Long-term indices are used widely for thermal comfort evaluation of existing buildings, fully or partly occupied, through monitored data (29, 31). Simulated data been used for comfort assessment during the design phase (29, 31). During the last decade, many researchers have used long-term indices for optimization of their case studies during the cooling period (30, 35-37). The optimization process refers not only to building elements but also to control strategies (objective and constraint functions).

In general, long-term indices may clearly interpreted only if all the boundary conditions explicitly analyzed (32). Different case studies should be harmonized before intercomparison (32). In addition, zoning definitions and guidelines for larger residential buildings (also non-occupied zones) have to be developed in future comfort Standards. Occupancy profiles and cooling periods definitions are crucial parameters for the long-term thermal comfort analysis (32, 38). Furthermore, Nicol et al. (2011) indicates that *"merely increasing the hours of occupation may 'solve' an overheating problem, which is clearly unrealistic"* (39). Long-term indices take into account temperature in total (25, 28). The indoor operative temperature calculation method affects the outputs considerably (29, 31). The operative temperature monitoring in many campaigns is not precise and depend on the sensitivity, uncertainty, and accuracy of the instrumentation (32). The comfort Categories are based on the quality of the building (28). Nicol et al. (2011) suggested relating the comfort Categories exclusively to the users' expectations (32, 39). Long-term indices cannot substitute a detailed and analytical thermal comfort analysis of a residential building (32). Regulations accept short deviations (mainly 5%) from defined comfort limits and thresholds (25, 38, 40).

An extended review of the overheating metrics is presented in (31, 32, 35). The most widely applied long-term overheating indices for "free-running" naturally ventilated dwellings are described below:

- Percentage of hours over a fixed temperature threshold (exceedance index)

These long-term overheating indices are static and based on fixed temperature thresholds (29, 31). The Chartered Institution of Building Services Engineers (CIBSE) have published the most widely applied overheating assessment guidelines based on fixed set points, specific examined periods, and appropriate weather data (38). The guidelines were reconsidered extensively in 2013 (Technical Memorandum 52; 40). The most applied thresholds are 25°C, 26°C and 28°C in room (bedroom and living room) and house level (31, 40). The Danish regulations use two different thresholds: 27°C and 28°C (residential buildings; 12). The 26°C threshold is used in many countries without discrimination of buildings to mechanically or non-mechanically cooled naturally ventilated, and it is based on Fanger's theory of thermal comfort (29, 31). All the indices transformed to percentages (%) based on the examined period (29, 31). These indices are simple, asymmetric, and easily understandable to non-technical users (29, 31). They are not based on Categories and comfort models and do not take into account the outdoor conditions and the adaptation mechanism (29, 31). In addition, these indices do not offer any information about the severity of the overheating problem (29, 31). Pane and Schnieders assessed the effectiveness of different thermal masses and glazing units with the use of static indices (41, 42).

- Percentage of hours outside the comfort range (POR)

The index "percentage outside the range-POR" cumulates the occupied hours (%) where the operative temperature is outside (higher and lower) the adaptive comfort model range for different Categories (equations 1-1, 1-2 and Table 1-1; 28). Without undercooling incidents, the index transformed to overheating indicator (23). The index is symmetric, category based and dynamic (29, 31). The index is an indicator of the overheating frequency and not of the overheating severity (29, 31).

- Degree-hours outside the comfort range (DHRS)

The index “degree-hours outside the range-DHRS” is similar with the previous index and is based on the same dynamic thermal comfort theory (28). The index cumulates the degree-hours (^{o}Ch) where the operative temperature is outside (higher and lower) the adaptive comfort model range for different Categories (equations 1-1, 1-2 and Table 1-1; 28). The index is dynamic, asymmetric, and category based (29, 31). Without undercooling incidents, the index transformed to overheating indicator, giving information about the severity of the indoor risk (29, 31).

- Difference between peak indoor and annual average outdoor temperature

The index DT is climatic condition dependent and offers no information about the frequency and severity of the overheating risk indoors (29, 31).

1.2.2. VENTILATIVE COOLING PERFORMANCE AND LIMITATIONS

Ventilation through natural or mechanical systems is an essential part of building operation for comfortable and healthy environments (32). Uncontrolled air infiltration and windows use in many cases are the only options for ventilation in residential buildings (43). In other building cases, more advanced and sophisticated passive or mechanical ventilation systems (exhaust or balanced systems with or without heat recovery) are installed (43, 44). The type of installed ventilation system and ventilation control strategy depends mainly on regulation requirements, climatic conditions, installation and operational cost, building and site characteristics, thermal loads, and design preferences (43). Balance between air quality and energy conservation in buildings is essential. The dominating ventilation system in residences in Europe is natural “stack or wind driven” ventilation (45). If the main concern of the ventilation system is the dilution of the indoor contaminants to “health and safe” levels, the choice of the system is predefined (43). In humid climates, the majority of the residential buildings are air-leaky and mechanical ventilation systems are cost ineffective (43). In Northern climates, buildings are airtight and mechanical ventilation systems are necessary to improve air quality with minimum air change rates (0.5 ach; 43). In warmer regions, buildings are also airtight mainly focused on hotter periods of the year (43).

The global energy use for cooling, only for residential buildings, represents less than 5% of the total needs (heating and cooling) of buildings (2010; 46). The global warming, the urban heat island effects, and the heat waves are estimated to raise this share to 35% in 2050 and 61% in 2100 (46). Argumentations supporting this statement are also the increased comfort requirements and living standards, the development of the air-condition industry and the globalization of the modern architecture (47, 48). Ventilative cooling in combination with other passive cooling methods like thermal mass activation, decrease of the internal gains, and solar shading control may be an energy-efficient solution to diminish and, in some cases (climatic conditions, building types), to eliminate overheating risk and cooling loads of residential buildings while maintaining high environmental quality indoors (32). In addition, occupants of naturally ventilated spaces suffer less from “sick-building” syndromes (23). Sufficient ventilation in buildings may remove excess internal and external gains, as well as, increase ventilation rates and internal air velocities, especially at night time, and thereby widening the thermal comfort acceptability (28, 32). Maximum acceptable indoor operative temperature with constant air velocity (1.2 m/s with personal control) is up to 33.9°C (Category II; 28).

Ventilative cooling performance and effectiveness depend mainly on the availability of sufficient temperature difference (indoor and outdoor temperature) and efficient coupling between thermal mass and the air heat sink (32). The mechanism of heat extraction through natural ventilation is straightforward (49). Achieving significant rate of heat removal is challenging mainly because of the low thermal capacity of the air (49). Thermal mass has been demonstrated to be highly effective in diminishing the diurnal daily variation of indoor temperatures (33). Unless thermal mass is linked with very intense night ventilation strategies, it can result in overheating risk as heat is maintained within the house as the outdoor temperature approaches the peak daily value (33). The means of diminishing internal gains are simple and used routinely in Southern climates to provide comfortable indoor spaces (33).

The possibilities of utilizing the free cooling potential of the external air mass increase considerably as cooling becomes a necessity (50). During transition months, the cooling potential of outdoor air is high (32). The draft risk is also high and, as a result, the developed control strategy needs to be able to address this barrier (32). During peak summer periods, the ventilative cooling performance decreases and depends on the opening characteristics (positioning and sizing), the site limitations (urban microclimate), the thermal characteristics of the building elements, and the heat transfer variation of the internal surfaces, the air distribution system, and the flow pattern (32). Humidity ratio and wind characteristics as well as speed and direction are also important for the successful application of night time ventilative cooling strategies (47).

A number of simplified methodologies have been developed the last years that enables the assessment of the cooling potential of different areas based on climatic data and building characteristics (32). Artmann et al. developed the concept of “climatic cooling potential-CCP” to evaluate the indirect night ventilative cooling potential for Europe (50). A more sophisticated method, which takes into account thermal inertia of the building for different types of constructions has been proposed and applied in (51). The cooling potential in Central and Northern Europe during most days of the year is high (32). In Mediterranean countries, night time natural ventilation may still be part of the hybrid ventilation control strategies (32).

State-of-the-art reviews and design guidebooks of natural ventilation prediction methods and applied ventilative cooling technologies and control strategies are presented extensively in (32, 47, 49, 52-57). The majority of the research work refers to non-domestic buildings (53, 54, 56). Information on domestic house applications is limited and only a minimum number of verified experimental cases have been reported (32, 47). Experimental analysis has been conducted either to test cells (47, 58-63) or to real case studies by monitoring campaigns (32, 47). Numerous energy performance simulation based research works have been presented, documenting the theoretical performance of ventilative cooling through sensitivity analysis (32). Santamouris et al. (2010) concluded that night ventilation control strategies may decrease the cooling load by 12 kWh/m^2/year on average (maximum 40 kWh/m^2/year; 32, 47, 64). The research was conducted in 214 air conditioned residential buildings, between 55 and 480 m^2 with night ventilation strategies (64). The air change rates varied from 2 to 30 ach (64). For the hot and humid climate of Israel, ventilative cooling decreases the indoor temperature by 3-6^{o}C in a heavy constructed non air-conditioned residential building (32, 65). For similar climatic conditions, Iran, the research team suggested 12 to 30 air change rates and avoidance of East and West openings (66). Research on full-scale experimental cases in hot-humid climate of Malaysia has shown that night ventilation may decrease the peak indoor temperature of the next day by 2.0-2.5^{o}C for different daily window use patterns (62). Night ventilation in social houses in Madrid through solar chimneys guaranteed indoor temperatures between 21-23^{o}C in night time (67). CIBSE suggests that, for natural ventilation design, 10 air change rates are reasonable and should be developed through well optimized and properly located window opening configurations (33). Achieving these ventilation rates with a mechanical system would be difficult as this is approximately 20 times the normal background rate of 0.5 ach (43). Larger fans and ducts are necessary, causing noise nuisance issues and increase of the installation cost and lost space (33). In addition, for 2°C temperature gradient and internal gains of 120 W, the air flow rate required to extract that amount of heat would be approximately 50 l/s (33). This example refers to the British climatic conditions and for a typical dwelling (33). A typical Australian single-family experimental house was examined for different natural ventilation strategies under the summer conditions of Sydney (68). The thermal needs of the building were diminished by 28.9% using natural ventilation control strategies at daytime and by 54.9% using natural ventilation during all day (68). A list of 26 buildings (residential and non-residential) in operation and under continuous monitoring investigation with natural ventilation and ventilative cooling technologies and applied control strategies is available in (32).

Critical barriers and limitations for ventilative cooling applications and control strategies are mainly the climate change and global warming, the urbanism (reduced natural driving forces), the heat island effects, and the increase of the air pollution through dust and contaminants (32, 69). Typically, it is not possible to open windows extensively in certain urban areas located close to highways or railways due to noise nuisance and security reasons (33). In rural areas, insects and pets also create problems. Intense outdoor conditions which cause problems to the indoor furniture and occupancy (e.g. strong winds, rain, and others) also restrict use of the openings (33).

In general, principles and control strategies for ventilative cooling are simple but the overall mechanism of ventilation is very complicated (32). Ventilative cooling simulation involves many uncertainties, and it is a challenging task to be verified by monitored data *in situ* (47, 70). Trade-off between preciseness, time and cost computational effort, and complexity is always an issue for consideration (47).

Occupants' behavior is identified as the number one factor for successful performance and effectiveness of ventilative cooling applications and control strategies (32). In passive low energy buildings, the influence of the occupants' behavior, preferences, and attitudes becomes more critical (71). According to Wallace et al. (2002), 87% of the total air change rates of buildings are related to the occupants' behavior, mainly on system use (72). Kvistgaard et al. (1990) and Bekö et al. (2011), who measured air change rates in 16 identical Danish dwellings and 500 bedrooms respectively, concluded that the different behavior of the occupants caused these large deviations in energy and comfort (73, 74). Openings use behavior is related with psychological, cultural, educational, social, and lifestyle factors (75-77). Indoor and outdoor conditions, daily patterns, and building and window characteristics are also key factors (32). In the literature, most of the proposed models were extracted from non-domestic buildings (field test studies) cumulating large data from heating, transition, and cooling periods (75-77). Environmental parameters (indoor and outdoor) and air quality indicators, mainly carbon dioxide, determine the window opening percentage (75-77). Window opening behavior models for single or multi-residential buildings are presented in (78, 79). The impact that the window use has to the building performance and energy use is examined in different moderate climatic conditions (80-83). Occupants' control on window openings causes unnecessary energy use and not optimal indoor conditions (84). Fabi et al. (2013) presented a framework for simulation of window opening behavior for dwellings in a building performance simulation (BPS) tool (85).

Ventilation controllability is an important barrier for the widespread adoption of passive ventilative cooling strategies through natural systems (20, 48). Automated control systems integrated in window configurations (façade and roof openings) are already the case for large scale, non-residential buildings (20, 86, 87). Automated window opening control systems with integrated straightforward heuristic algorithms, hereafter called "window systems" may considerably diminish the energy waste and optimize the indoor environment (20, 88, 89). In addition, window systems as integrated part of the new façades cause minimum aesthetic impact during renovation processes. A continuously higher penetration of the intelligent window systems in dwellings is expected in the next decade worldwide, transmuting them into smart homes (20, 86, 88). Window systems are building automation systems (BAS) with limited human intervention, which real-time monitor, control, and optimize the indoor spaces and the energy costs (87). BAS are able to communicate with each other under central supervision and may give feedback and suggestions to the user for optimal performance (87). Data collection improves the commissioning process and the information management (decision making; 87). BAS have to be oriented to users' behavior patterns and match the occupants' needs (90). System characteristics that improve the level of trust between the user and the domestic system are the simplicity, the transparency, the preciseness, the predictability, and the usability (90). Individual control opportunities have to be integrated to the system for the maximum acceptance and consent by the users (90).

Window systems with rule based control (RBC), "IF (condition)-THEN (action)", are the industry standard (91, 92). Martin et al. (1996) concluded that complex algorithms and control strategies for night ventilation in many cases do not perform better than simple ones (70, 93). In addition, the setting of the parameters of the control strategies in many cases proved more important than the strategy itself (70). Window systems with advanced control strategies are based on either the predictive control theory or the computational intelligence (neural networks; 94). These approaches highly depend on the fidelity of the model and the simulation assumptions (94). Computational power also is needed and a large amount of data are extracted (94). Advanced window systems are not cost-effective for small and medium-sized residential buildings, and they are complex for domestic users (94, 95).

Finally, literature review indicates that there are no mature and validated BPS tools which may represent the most sophisticated and advanced ventilation control strategies (32, 96). Control simulation in BPS tools needs to represent precisely how actual algorithms are applied (20, 96). Idealized control patterns cannot substitute them effectively (20, 96).

1.3. OBJECTIVES OF THE THESIS

The objectives of this research study are to investigate, highlight, and address the challenges related to diminish of the overheating risk (likelihood, severity, intensity, and duration) in energy renovated single-family houses under different European temperate climatic conditions as well as to develop an efficient and sustainable ventilative cooling solution and control strategies (full concept) for this type of buildings, avoiding mechanical cooling systems installation. The developed concept should improve and optimize the ventilative cooling capacity of the existing systems. Control strategies have to fulfill the occupants' needs. However, it is more effective if the developed control strategies for dwellings are focused on combined operation of ventilative cooling, solar shading, and thermal mass activation. The analysis is focused in Danish climatic conditions. Other temperate climates will be included and examined in the analysis.

The following research questions will be answered to support these objectives:

- Do energy renovation measures and solutions contribute to the overheating risk, in room and building level, of single-family houses in temperate climates?
- Can ventilative cooling method and control strategies through window opening systems diminish the overheating risk and optimize the indoor environment of single-family houses in temperate climatic conditions?
- Can the new developed automated window opening control concept (system and control strategies) improve the indoor thermal environment of a deep renovated single-family house in temperate climatic condition? Can this be done without any significant compromise to the air quality condition and without additional energy use during the cooling period?

1.4. THESIS OUTLINE

Chapter 1 presents the background and objectives of the research study. In addition, provides a literature review regarding overheating definitions and thermal comfort assessment metrics and ventilative cooling performance, effectiveness, potentials, and limitations within building design.

Chapter 2 presents and highlights through numerical analysis the overheating risk of single-family houses under different energy renovation measures for different temperate climates.

Chapter 3 investigates and highlights through numerical analysis the ability of different ventilative cooling control strategies in order to effectively address the overheating risk in energy renovated single-family houses in temperate climates.

Chapter 4 presents a new developed automated window opening control system (solution and control strategies) and investigates its ability to improve the indoor environment of a deep energy renovated house in Northern temperate climatic conditions during the peak cooling season.

Chapter 5 compares and statistically correlates the overheating metrics for the total of the numerical analysis.

Chapter 6 provides general conclusions drawn from the research study.

Chapter 7 summarizes and recommends future research directions.

Appendix I-V contains the collection of the journal and conference articles, which refer to the research study.

CHAPTER 2. ENERGY RENOVATION AND OVERHEATING RISK ASSESSMENT: A NUMERICAL ANALYSIS

It is fundamental for building owners that the energy interventions and improvements are accompanied with high quality indoor environment, both in terms of air quality and thermal comfort. The objective of this chapter is to investigate and highlight the overheating risk of single-family houses, in room and building level, under different energy renovation measures for different temperate climatic conditions. The analysis is conducted for four reference dwellings in representative climatic conditions of Northern and Central Europe. The examined reference houses have high market and energy renovation potential in the coming years. This chapter describes in detail the case studies, the energy renovation measures, the performance indicators, and the simulation assumptions.

2.1. CASE STUDIES

The overheating risk is assessed in four different representative - in national level - single-family houses and climatic conditions (9, 97): Austria (Vienna), Denmark (Copenhagen), South France (Marseille) and the U.K. (London). Figure 2-1 presents the daily average ambient temperatures (as exported from updated Energy Plus weather files; ^{o}C) of the examined cities during a year (9, 98). The building stock of these examined countries is equal to the 33% of the in-use European (EU-28) buildings (4). In addition, all the examined countries have very efficient regulations for energy renovations in buildings and two of them (the U.K. and France) have faced human losses from unusual high summer temperatures in previous years (9, 22). Future projections conclude that cities of Central Europe will face unusually high ambient temperatures in the coming years (9, 22).

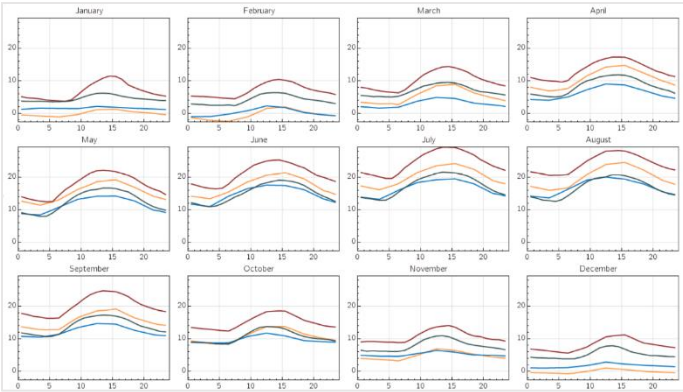


Figure 2-1 Daily average (all months) ambient temperatures (y axis: °C) of the examined cities (Copenhagen: blue, London: green, Marseille: red, and Vienna: orange). The weather files were edited in DView tool 2.0.0.5, National Renewable Energy Laboratory, 2017.

Building typologies is a new tool for policymakers and stakeholders to calculate the current and future building energy performance on regional and national levels (99, 100). The "Typology Approach for Building Stock Energy Assessment-Tabula" project has a harmonized structure and describes analytically archetypes of 13 European countries, categorized in periods and building types (detached, terraced, apartments and multifamily buildings; 99). The Tabula project focuses on residential buildings and suggests possible renovation scenarios based on the regulations of each country and the saving potentials of the existing buildings (99). The Danish and the South French case studies (representing more than 1.6 million dwellings in total) are real buildings from 1970s and 1980s respectively as extracted from the Tabula project (4, 9, 10, 101). The Austrian and U.K. case studies (representing more than 1.7 million dwellings) are hypothetical average dwellings approximately from the middle of the previous century (4, 9, 101-103). The case studies were used and analyzed at the official reports of the examined countries to the European commission, and they are based on deep statistical analysis of the energy certificates (9, 102, 103).

In general, the case studies are heavy-weight constructions with materials and construction techniques of these periods (9). The insulation was placed inside the walls (foam insulation) and in the attic (mainly mineral wool; 9). The dwellings have high thermal mass and high thermal bridging (9). In most of the dwellings, the window glazing is single and the frame is wooden (9). The opening percentage for every orientation is extracted from the sources (9). Table 1-Appendix I presents the thermal (U-value and g-value) and technical characteristics of the examined dwellings (base case; 9). Houses have no mechanical ventilation or active cooling systems (base case; 9).

2.2. ENERGY RENOVATION MEASURES AND PHASES

This research study examines two different renovation group packages:

- Measures which refer to the efficiency of the building elements and the envelope (Group A)
- Measures which refer to the mechanical ventilation and shading systems (Group B)

Building owners mainly renovate their properties in steps (e.g. windows, ceiling and others) for economic reasons (9, 104). In many cases, these renovation steps take months or years (9, 104). In addition, they renovate their dwellings either to reach the existing energy regulations (minimum requirements) or to reach very efficient energy targets and schemes (9). This numerical analysis is divided in three phases (Table 1-Appendix I; 9). The first phase is the initial base case study as extracted from the national reports and Tabula project (section 2.1; 9). In the second phase, the dwellings are renovated in steps, according to the energy efficiency regulations of each country (9). The third phase is the reference values of a very efficient international energy target or scheme (9). This process creates a matrix of 8-10 different variants for every dwelling (Table 2-Appendix I; 9).

The improvement of the efficiency of the elements (insulation materials) is performed externally for the exploitation of the thermal mass of the building (9). The "airtightness renovation step" is a process which related with all the intermediate steps of the renovation (9). In this analysis, it is presented as a discrete step to emphasize the contribution of this process to the increase of the overheating risk of a dwelling (9).

The renovation of the dwellings is accompanied in many cases with the installation of shading systems at the openings and mechanical ventilation systems, oriented mainly to the heating period and daylight control (Group B; 9). The effects of this renovation package to the overheating risk of two case studies (South French and Danish) during summer and transition months are also examined (9).

Three shading systems are analyzed (9):

- Internal venetian blinds with high reflectivity
- External slat blinds with high reflectivity
- Fixed pergolas and awnings

The movable shading systems are in use during the non-occupied hours for all the windows and orientations (Table 3-Appendix I). The mechanical ventilation system is represented through increased airflow rates from the basic value, 0.5 ach, to 1.5 ach (three intervals; 9, 43). The airflow rates are applied to all rooms during all day (9).

2.3. DYNAMIC BUILDING PERFORMANCE SIMULATIONS

The dynamic building performance simulations for the overheating risk assessment of the indoor spaces of the case studies are conducted with the use of the calculation engine Energy Plus, version 8.1, through an add-on interface DesignBuilder, version 4.2 (9, 105). The software complies with the European regulations and Standards (9, 105). For the calculation of the heat conduction of the elements and the natural convection heat exchange, the CTF (conduction transfer function) algorithm, TARP method (externally), and DOE-2 method (internally) are used (default options; 9, 105). Finally, a 26-day warm-up for the building performance tool and 4 steps per hour are used for accuracy reasons (9, 105).

The case studies are simulated as “free-floating” buildings during the transition and summer months (9). For the rest of the period, a minimum indoor operative temperature is set (20^{o}C; 9). The non-overheated period is outside of the interest of this research study (9). The air change rate is set to 0.5 ach (43). The buildings are oriented to the East-West orientation (typical scenario) and two identical rooms are developed (6.3 m^{2} of net floor area) facing the South-West and the North-East orientations (room analysis; 9). The occupancy and internal heat gains (net floor area) weekly profiles reflect a typical 5-member working family (Table 4-Appendix I; 9, 106, 107).

2.4. RESULTS

In this analysis, two well-documented and widely applied metrics for the assessment of the overheating indoors are used (9). The first one is the POR index (Category II) and the second one is the exceedance index with two static benchmarks, 26^{o}C (bedrooms and building) and 28^{o}C (living room; 9). Both metrics are described analytically in section 1.2.1. No undercooling incidents were observed during the examined periods (9). The overheating (%) refers to the entire year (9). Renovation measures extend the overheating period outside the typical summer limits. These “tails” of the overheating incidents are interesting to be identified and highlighted. Both metrics refer only to occupied hours (Table 4-Appendix I; 9).

Figures 2-2 (a-d) present the overheating (%) of all the examined case studies for both metrics, different renovation variants and phases, and examined rooms. For the Austrian and the U.K. dwellings (Figures 2-2 (a and d)), the renovation variants 1 to 3 (window, ceiling, and wall improvements) of phase two slightly decrease the discomfort conditions and overheating risk indoors (both metrics; 9). The g-value coefficient seems to be more critical parameter compared to the U-value of the openings as far as the decreasing of the overheating risk is concerned (variants 2 and 6; 9). Floor insulation and airtightness improvement (variants 4, 5, 7, and 8) increase highly overheating (both metrics; 9). For the Danish and South French dwelling

(Figures 2-2 (b and c)), the outputs and conclusions are similar with those of the other examined case studies (9).

In the Austrian case, the overheating period (dynamic metric) is extended from June-August (phase 1); to May-October (phase 3; 9). In the U.K. and Danish dwelling, the overheated periods remain almost the same between phases (May to September/October; 9). At the South French dwelling, the overheating period is extended from May-September (phase 1) to April-September (phase 3; 9). Increase of the energy efficiency of the envelope also affects (increases) average and maximum indoor operative temperatures (Figure 2-3; 9). The Danish house shows the highest maximum operative temperatures among all the cases for every renovation phase (9). The South French house shows the highest values for both renovation phases with the static method, and the U.K. house shows the highest values with the dynamic one (9). The static metric shows higher outputs compared with the dynamic one for every renovation variant and examined case and room (9). Both metrics for the U.K. case study show similar outputs (9).

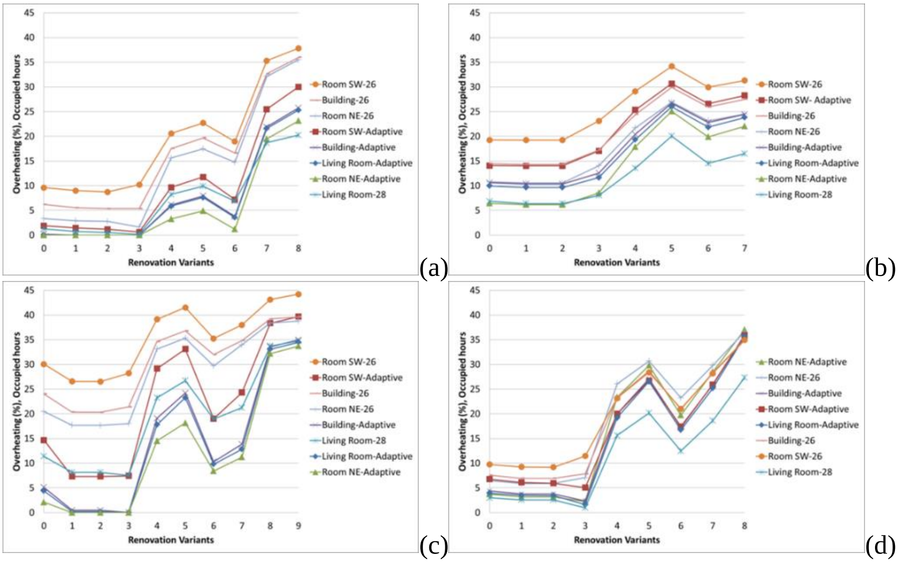


Figure 2-2 Percentage of overheating (%) for different renovation variants (Group A) in room and building level for both metrics, for all the case studies (a: Austria, b: Denmark, c: South France, and d: U.K.; 9: p.143-144).

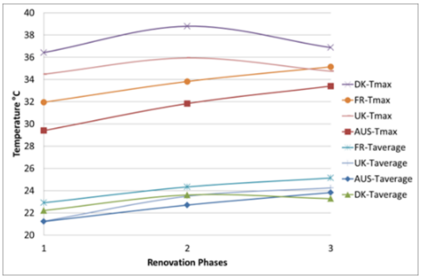


Figure 2-3 Yearly average and maximum operative temperatures (building level) for all the examined case studies, for different renovation phases 1, 2, and 3 (9: p.144).

Group B renovation measures are antagonistic and diminish overheating incidents indoors (9). Figures 2-4 (a, b) and 2-5 (a, b) present the overheating (%) of the two examined case studies (Denmark and South France) for both metrics, different renovation variants, and phases (1, 2, and 3) and ventilation rates or shading systems (external, internal and fixed; 9). The increase of the ventilation rate of the space significantly diminishes the incidents indoors for both cases (9). The higher the envelope renovation of the house, the higher the effectiveness of this measure (9). The external shading systems diminish the incidents by 50% in the Danish dwelling for both metrics (internal blinds 25%; 9). For the South French case, shading strategies are not very efficient (9). Overheating risk in Southern temperate countries was mainly related with outdoor ambient temperatures and less with solar gains and radiation (9). Comparable outputs were also extruded by room level analysis (9). Both metrics show equivalent results for the Danish dwelling and more discrepancies for the South French dwelling (9). Renovation measures of Group B (systems) also significantly affect (decrease) the indoor average and maximum operative temperatures and overheating period (9).

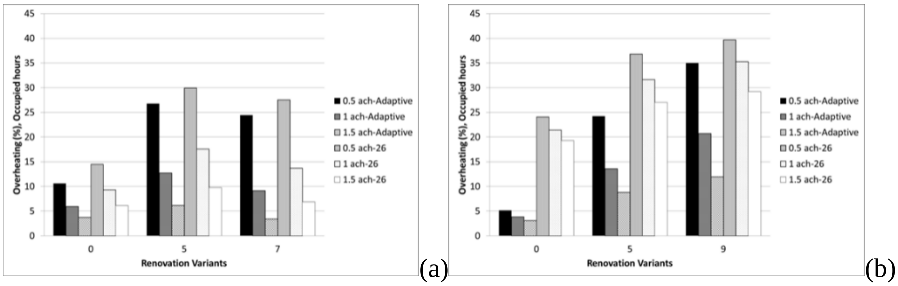
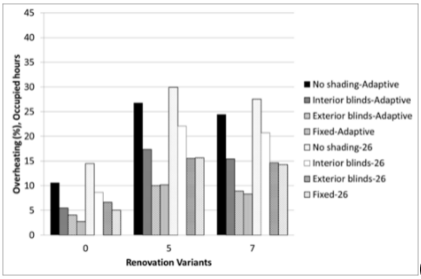
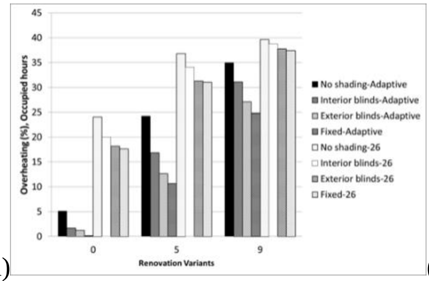


Figure 2-4 Percentage of overheating (%) for different renovation variants and phases (Group B) and ventilation rates in building level for both metrics, for two case studies (a: Denmark, b: South France; 9: p. 145).



(a)


(b)

Figure 2-5 Percentage of overheating (%) for different renovation variants and phases (Group B) and shading systems in building level for both metrics, for two case studies (a: Denmark, b: South France; 9: p.146).

2.5. CONCLUSIONS

The numerical analysis of this chapter indicates that the improvement of the efficiency of dwellings (to decrease energy use for heating) in temperate Central and Northern European climatic conditions increases the overheating incidents indoors, the average and maximum indoor temperatures in room and building level, and the overheating period (9). These numerical analyses confirm the findings of a number of post-occupancy comfort studies in residential buildings in climatic conditions of Northern and Central Europe during the last decade. Alarming measures are the insulation of the floor elements and the improvement of the airtightness (related with all the renovation variants; 9). Neutral contribution (slightly positive) offers the increase of the efficiency of the ceiling and wall elements (external insulation) of the envelope (9). Positive contribution offers diminishing of the g-value of the windows inside the existing glazing regulation limits (9). Rooms on specific orientations and with high window-to-wall ratios have higher risk than the total building on average (9). Thermal comfort analysis in room level (critical rooms and occupied rooms with minimum volume) for energy renovation projects is recommended (9). This thermal comfort analysis should be integrated on national regulations and comfort Standards in the future (9).

Both metrics show similar patterns and critical energy renovation measures (9). Typically, static metric shows higher values (9). The static metric shows small discrepancies for examined case studies in the Northern climatic conditions (the U.K. and Denmark; 9). The discrepancies become more significant as we examine Southern climatic conditions (9).

Shading systems, mainly external, applied with simple control strategies may diminish the overheating effectively, especially in the Northern temperate climatic conditions (9). In terms of overheating risk, the most effective renovation measure from the examined ones is the installation of the mechanical ventilation system and the application of high air change rates, for every case study and renovation phase (close to or higher than the capabilities of the system for domestic use; 9). The higher the efficiency of the house, the higher the effectiveness of this action, in overheating terms (9).

The increase of the mechanical ventilation air change rates, during all day, considerably improves the indoor environment, in terms of overheating risk and air quality, but also increases the energy use of the dwelling (9). Ventilative cooling solutions and control strategies that use natural opening systems may be proved very effective solutions for these temperate climatic conditions, without increasing the building energy costs.

For further information, please refer to Article 1-Appendix I: "Overheating risk barriers to energy renovations of single family houses: Multicriteria analysis and assessment."

CHAPTER 3. VENTILATIVE COOLING CONTROL STRATEGIES: A NUMERICAL ANALYSIS

This chapter extends the numerical analysis of the previous chapter and investigates and highlights the ability of different ventilative cooling control strategies in order to effectively address the overheating risk in energy renovated single-family houses in temperate climatic conditions. In terms of overheating risk, the performance of different residential building oriented ventilative cooling control strategies is examined for different indoor natural ventilation cooling set points, façade and roof window opening percentages, wind conditions and opening discharge coefficients. The case studies are similar (small deviations) to those described in the previous chapter (Danish and South French dwellings, section 2.1). For performance indicator, the POR index (Category II) is used (section 1.2.1). No undercooling incidents are observed for the total of this numerical analysis.

3.1. DYNAMIC BUILING PERFORMANCE SIMULATIONS

Wind and stack effects are simulated in multizone buildings with accuracy by the development of the airflow network (AFN), nodes, and resistances, scholastically (70). Airflow components like horizontal or vertical openings, cracks, flow controllers, fans, and others are linked to these sets of nodes developing the network (70). For this analysis, the developed models are simulated as well-mixed zones with uniform zone temperatures, homogenous air properties, and hydrostatically varying pressures (21, 70). The pressure differences that create air movement through windows, doors, cracks, and throughout the building zones are calculated internally in every time step (21, 70, 105, 108).

Wind pressure coefficients (C_p) are input values in the AFN and are associated with the external air nodes (109). The wind pressure coefficients are related with the wind direction, geometry, and position of the surface and side exposure-terrain (109). Literature review suggests a range of values for discharge coefficient (C_d), varying between 0.3 and 0.8 (32, 105, 109). In this research study, two values for discharge coefficient are used: 0.45 and 0.65. Table 1-Appendix I presents the infiltration rates (50 Pa pressure difference) of the examined case studies (9). Default values for flow coefficient and flow exponent are used (70, 105). Doors are simulated as 50% open, 5% of the occupied time. For the part of the analysis without wind-driven ventilation, the wind factor of the tool is set to zero (Figure 3-1).

3.2. CASE STUDIES

The case studies, Danish and South French dwellings, are similar to those described in the previous section 2.1 (Figure 3-2) with small deviations at the thermal and technical characteristics (Danish case, Table 1-Appendix V; 12, 21). The case studies energy renovated deeply and high-efficient creating two different renovation scenarios (Table 1-Appendix I and Table 1-Appendix V; 9, 21). The full height of the dwellings is exploited and three South-oriented roof windows (1m^2 each) are simulated. The window openings cover the 10-35-10-0% (9.2% in total) and 20-20-0-10% (7.2% in total; North-South-East-West) of the external walls of the Danish and South French dwelling respectively (21, 101).

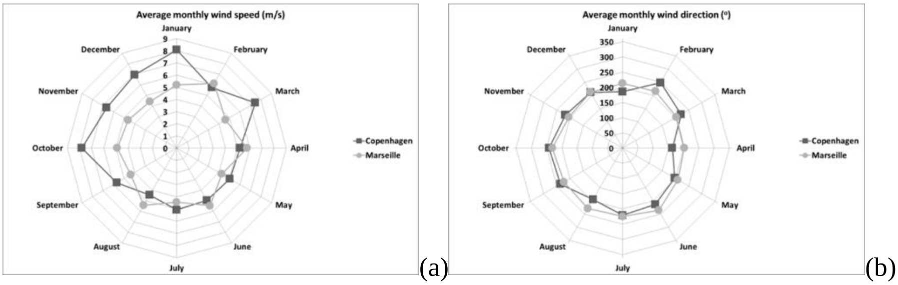


Figure 3-1 Average monthly wind speed (a, m/s) and wind direction (b, °) for the examined case studies, Copenhagen (Denmark) and Marseille (South France).

Figure 3-2 Examined case studies (a: Denmark and b: South French; 101).

3.3. CONTROL STRATEGIES

3.3.1. MANUAL WINDOW OPENING

A number of window opening behavioral models have been developed in the last decades (75-79, 110). The majority of the developed models have been created from monitoring campaigns in office buildings and their use has extended to domestic environments (110). The validity and accuracy of these models are uncertain mainly because of the limited examined population (contextual factors) or the poor description of the examined cases and, consequently, the transferability to other types of buildings with different users and on different climatic conditions is questionable (111). Occupants of dwellings tend to open the windows, mainly for indoor air quality reasons and as a result of a daily pattern at specific times during the day all year (21, 62, 104, 112). For this research study, the “typical” manual window opening (Table 3-Appendix V) is applied to all the openings (façade and roof) of the case studies, independently from the outdoor environmental conditions (21).

3.3.2. AUTOMATED WINDOW OPENING

The automated window opening control strategy for ventilative cooling is based on indoor operative temperature, indoor natural ventilation cooling set points, and ambient temperatures (21). The windows in every zone open when the ambient temperature is lower than the indoor operative temperature and when the indoor operative temperature is over an indoor natural ventilation cooling set point (21). This control strategy is applied to outdoor temperatures higher than 12.5ºC (21, 113).

This research has examined automated window opening as part of three different solutions (21):

Exclusive automated control:

- Automated control during the occupied hours (Table 2-Appendix V)
- Automated control during all-day

As part of a mixed control:

- Automated control during the non-occupied hours and at night from 00:00-7:00 and manual control (Table 3-Appendix V) during the occupied hours

All three automated or mixed-automated control strategies are compared with two basic ventilation solutions: manual use of window openings and mechanical ventilation system (0.5 ach, all day use; 43), in terms of overheating risk (21). Mechanical ventilation systems are widely installed in new or renovated residential buildings in temperate climates, mainly for indoor air quality reasons during the heating period (45). Typically, occupants do not use both mechanical ventilation systems and openings as a result of the strict directions of the installers and manufacturers (21, 104).

Ventilative cooling effectiveness in residential buildings are limited due to a number of constraints and barriers (32). The performance analysis of this research study is conducted to both case studies (Danish and South French) and renovation scenarios (Table 1-Appendix I and Table 1-Appendix V) and covers four parameters of investigation (Table 3-1):

- Indoor natural ventilation cooling set point
- Discharge coefficient
- Wind effect
- Percentage of window opening

The different indoor natural ventilation cooling set points are only examined for the first automated control strategy, and the outputs are used as a reference to the other control strategies (21). The window opening percentage refers to the percentage of the windows that opens for ventilation (21).

Table 3-1 Ventilation parameters for analysis.

Parameter	**Manual control**	**Mixed control**	**Fully automated control (occupied)**	**Fully automated control (all day)**
Discharge coefficient (0.45-0.65	Yes	Yes	Yes	Yes
Wind effect-No wind effect	Yes	Yes	Yes	Yes
Window opening (10, 50%)	Yes	Yes	Yes (additionally 30%)	Yes
Indoor natural ventilation cooling set point (22-24°C and 23-25°C)	-	22°C and 23°C	Yes	22°C and 23°C

3.4. RESULTS

The initial part of the analysis refers to the fully automated control strategy (occupied hours). The numerical analysis covers different indoor natural ventilation cooling set points, wind conditions, window opening percentages, and discharge coefficients (Table 3-1). For both dwellings, three different indoor natural ventilation cooling set points are examined (Table 3-1). The examined ventilation parameters remain constant for the total of the analysis.

Figures 3-3 (a, b) and 3-4 (a, b) present the overheating assessment (adaptive method, %) for both case studies and renovation scenarios (21). The results show overheating incidents for almost every case and scenario for all the ventilation parameters of the analysis. As expected, the South French house shows higher values compared to the Danish case for comparable parameters (climate related). The decrease of the indoor natural ventilation cooling set points, the increase of the discharge coefficient of the windows, the presence of the wind effect, and the increase of the window opening decrease the overheating incidents for both examined dwellings and scenarios (21). The maximum overheating for the Danish house, close to 10%, is related with the deep renovation scenario (21). The differences of the values for the South French house between the minimum natural ventilation cooling set points (22ºC and 23ºC) are negligible (not presented in this research study). The maximum value for the South French dwelling is 23%, and it occurs at the nZEB renovation scenario. Five values (deep renovation) and four values (nZEB renovation) in the Danish case and twelve values (deep renovation) and nine values (nZEB renovation) in the South French case do not fulfill the minimum requirements of the comfort European Standard (5%; 25). All the cases that do not comply with the requirements are related with the absence of wind effect (urban conditions) and low window opening percentages (Danish case). For the South French dwelling, the examined cases that do not comply are mixed and contain different ventilation settings and parameters.

Based on this analysis, the most critical parameters for diminishing of overheating incidents are the window opening percentage and the presence of the wind. The indoor natural ventilation cooling set point and the discharge coefficient are low and medium critical factors respectively. For almost all the cases of the analysis, the nZEB renovation scenario presents lower values of overheating compared to the deep renovation scenario (21). The only exception is the South French dwelling with low opening percentages for every examined indoor natural ventilation cooling set point and without the wind effect (both discharge coefficient settings).

On average, the decrease of the overheating is 74.9% for increase of the window opening percentage from 10% to 30% and 85.8% for increase of the window opening percentage from 10% to 50%. The increase of the window opening percentage does not decrease the overheating incidents proportionally (21). The major effectiveness of the ventilative cooling happens at the initial window opening percentages (21). In general, for indoor conditions without major undercooling incidents and violations, the lower value of the indoor natural ventilation cooling set points range (22ºC) is suggested as a minimum set point for automated window opening control systems in temperate climates. Overheating incidents show an abrupt increase over these upper indoor natural ventilation cooling set points (not presented in this research study).

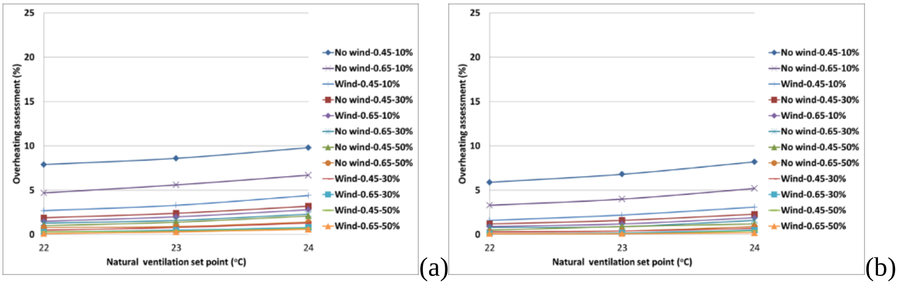


Figure 3-3 Overheating assessment (adaptive method, %) for a: deep renovation scenario and b: nZEB scenario, for different indoor natural ventilation cooling set points (°C), wind effects, discharge coefficients (0.45, 0.65), and opening percentages (10%, 30%, 50%, Danish dwelling).

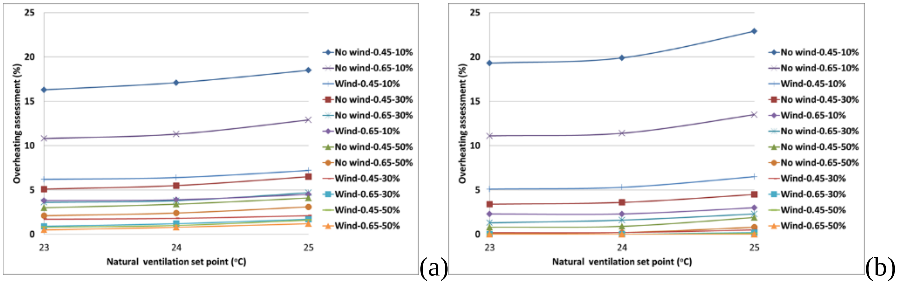


Figure 3-4 Overheating assessment (adaptive method, %) for a: deep renovation scenario and b: nZEB scenario, for different indoor natural ventilation cooling set points (°C), wind effects, discharge coefficients (0.45, 0.65), and opening percentages (10%, 30%, 50%, South French dwelling).

Table 3-2 presents the minimum and the maximum values of daily average air change rates (ventilation) for both case studies and renovation scenarios of this analysis. Table 3-2 presents air change rates from May to September (common overheating period). In many cases, minimum air change rates from ventilation are lower (also zero, Danish case study) than air quality ventilation limits of internal spaces of residential buildings (0.5 ach; 43). The results are better for the south French case study. The reason for this limitation is the cold outdoor conditions during the examined period (May and September) for the Northern temperate climates. For this reason, it is suggested that the automated window opening control systems based on indoor natural ventilation cooling set points be combined with demand control ventilation systems for fulfillment at least of the minimum indoor air quality requirements. In addition, the maximum daily air change rates in some cases are high, resulting in high air velocities indoors. These conditions cause discomfort to users in real cases. The automated window opening control systems have to be supported by override closing systems.

Table 3-2 Minimum and maximum values of daily average air change rates (ach) for both case studies and renovation scenarios (May to September).

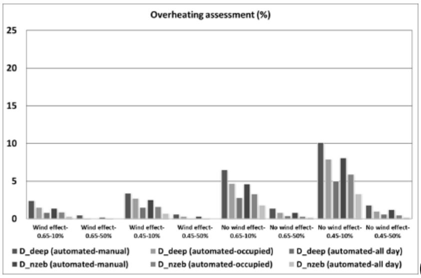
Case study	**Renovation scenario**	**Minimum air change rates (ach)**	**Maximum air change rates (ach)**
Danish	deep	0.0-0.2	2.1-28.9
	nZEB	0.1-0.6	2.0-28.5
South French	deep	0.3-1.4	1.7-48.8
	nZEB	0.5-1.5	1.7-43.7

Figures 3-5 (a, b) present the overheating assessment (adaptive method, %) of both case studies and renovation scenarios for the three different automated or mixed-automated control strategies and ventilation parameters (Table 3-1). The indoor natural ventilation cooling set points are set to the minimum values of the previous analysis, 22^{o}C and 23^{o}C respectively (21).

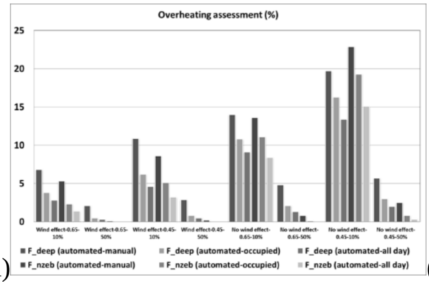
The automated control strategy, activated all-day, shows the lowest overheating incidents for both case studies, scenarios, and analyzed ventilation parameters. This control strategy exploits almost the full ventilative cooling potential of the two climatic conditions (32). For the Danish case, there is full compliance with the comfort Standards for every examined ventilation parameter (25). Three cases for every house (both scenarios) present no overheating incidents at all (21). Similar to the previous analysis, the out of the limits of the comfort Standards results are related to the absence of wind effect and low window opening percentages (South French case).

The mixed, manual and automated, control strategy is the least effective among the three examined solutions (21). The reason is that the user allows warmer air (no temperature control) to enter the space for air quality reasons during the occupied period and that the period for ventilative cooling (night time) is not sufficient to diminish the overheating (21). In total for all three automated control strategies and the total analysis, the South French case study shows plenty of results (10 for deep scenario and 9 for nZEB scenario) that do not comply with the overheating deviation limits of the comfort Standard (3 for deep scenario and 2 for nZEB scenario and the Danish case; 25). The different results between the two most effective automated control strategies illustrate the fact that ventilative cooling is possible also during the morning and noon hours for both climates (21). On the other hand, a fully automated control strategy activated during all-day raises serious concern as far as the security of the dwelling (21, 32).

Ventilation through mechanical systems results in overheating 33.4% and 35.8% for the Danish house and 37.4% and 52.6% for the South French house for the two renovation scenarios respectively (21). Similar high overheating incidents are also calculated with the use of the typical manual window opening (21). None of the results of the manual use for both dwellings and scenarios fulfill the minimum requirements of the comfort Standard (25).



(a)



(b)

Figure 3-5 Overheating assessment (adaptive method, %) for different automated or mixed-automated control strategies and ventilation parameters (wind effects, discharge coefficients (0.45, 0.65) and opening percentages (10, 50%)) for both examined case studies a: Danish dwelling and b: South French dwelling, and both renovation scenarios (deep: deep renovation scenario, nZEB: nZEB renovation scenario).

Figures 3-6 (a, b) present the effectiveness (average, maximum, and minimum values) of every examined automated control strategy compared with the basic examined ventilation patterns (mechanical ventilation and manual window opening), for different case studies and renovation scenarios for the total of the analysis (Table 3-1). On average, for the Danish case, the effectiveness of the automated control strategies is higher than 80% (for all the cases) and 90% for 10 out of 12 cases (21). For the French case, the effectiveness (average value) is over 70% (for all the cases). The comparison of the results among the manual window opening and the mixed automated control strategy highlights the importance of the night ventilative cooling in the design of an energy renovated house without overheating risk (21).

Figure 3-7 presents the contribution of the discharge coefficient to the overheating for the total of the analysis. All the results refer to comparable analysis (case study, renovation scenario, and ventilation parameters). The correlation of the results is almost linear and with coefficients of determination, 0.98 and 0.96, for the Danish and South French house respectively. By combining the results, the inclination of the line is 1.2 and the coefficient of determination is also high (0.97). In general, the decrease of the discharge coefficient from 0.65 to 0.45 increases the overheating risk on average by 20% for both climatic conditions and case studies.

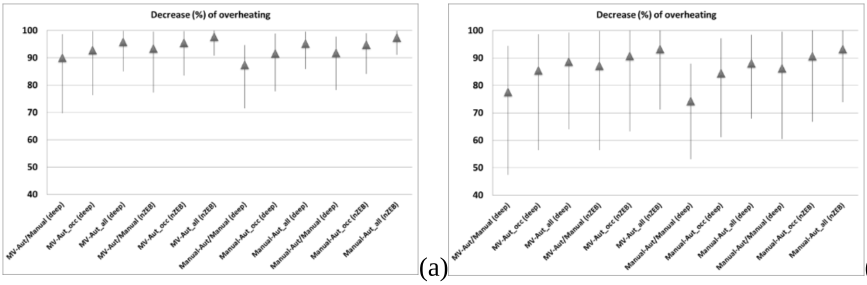


Figure 3-6 Effectiveness (decrease of overheating, %) of different automated control strategies for two renovation scenarios for the total of the analysis, a: Danish dwelling and b: South French dwelling, (minimum, average, and maximum values; manual: manual window opening, MV: mechanical ventilation, aut: automated window opening, occ: activated during the occupied hours, all: activated during all-day, deep: deep renovation scenario, nZEB: nZEB renovation scenario).

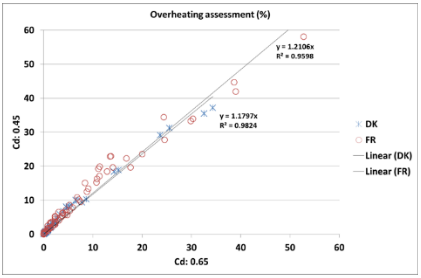


Figure 3-7 Contribution of the discharge coefficient (0.45, 0.65) to the overheating for the total of the analysis (DK: Denmark and FR: South France).

3.5. CONCLUSIONS

The numerical analysis of this chapter highlights the effectiveness and the ascendancy, in terms of overheating, of the automated window opening control systems with simple heuristic ventilative cooling control strategies based on indoor natural ventilation cooling set points and monitoring of the outdoor conditions, against indoor air quality based manual controlled ventilation and mechanical ventilation systems (21). The performance of the examined automated control strategy amplifies with the increase of the application time (also during the morning time; 21). In colder temperate climatic conditions (Nordic countries), automated window opening control systems may significantly diminish the overheating risk indoors (21). In the hotter temperate climates (Central Europe), these systems may not be sufficient to eliminate the risk alone, but combined with other passive cooling methods, like shading and activation of the thermal mass. The most critical ventilation parameters for decreasing of overheating incidents are the window opening percentage and the presence of the wind (21). The indoor natural ventilation cooling set point and the discharge coefficient are of low and medium importance respectively (21). The major performance of the ventilative cooling method (automated control) results in at the initial window opening percentages (21).

In addition, the more efficient the dwelling is, the more effective the ventilative cooling strategy is with automated window opening control in terms of overheating risk (21). The examined automated window opening control systems in colder temperate condition have to be combined with demand control ventilation systems for fulfillment of the minimum indoor air quality requirements during the cooling period (21). Additionally, automated systems have to integrate override control systems for non-acceptable extreme situations (21). The calculated values of this research study may be used as reference targets or supporting material for similar automated window opening control systems installed in residential buildings in similar temperate climatic conditions (21).

For further information, please refer to Article 5-Appendix V: "Control strategies for ventilative cooling of overheated houses."

CHAPTER 4. WINDOW SYSTEM DEVELOPMENT AND APPLICATION

The objectives of this chapter are to present a new developed automated window opening control system (solution and control strategies) and to investigate its ability to maintain or improve the indoor environment in terms of overheating and air quality of a single-family energy renovated house in Northern temperate climatic conditions during the peak cooling season. The new window system has integrated heuristic passive cooling control strategies, and it is based on real-time data monitoring of the environmental parameters inside and outside the house (104). This analysis directly compares the performance of manual control against the automated control of the window openings for a fully occupied real house from 1930s in temperate climate and for two complete peak summer periods (monitoring campaign from June to August of 2015 and 2016): one without the automated system implemented and one with the window system installed at the roof windows of the dwelling (104). Static and dynamic overheating metrics are used in room and building level. Performance indicators for the air quality are the carbon dioxide concentration (ppm) and the relative humidity (%).

4.1. CASE STUDY

The examined residential building is a yellow brick, two-storey detached dwelling from 1937 and located in a suburban area North of Copenhagen, Denmark (Figures 4-1 (a, b); 104). The house is 172.4 m^2 (gross area) and 363.3 m^3 (net volume area) with a basement (104). The dwelling is occupied by a working family, four members in total (104). This building is representative of the Danish residential building stock (104).


(a)

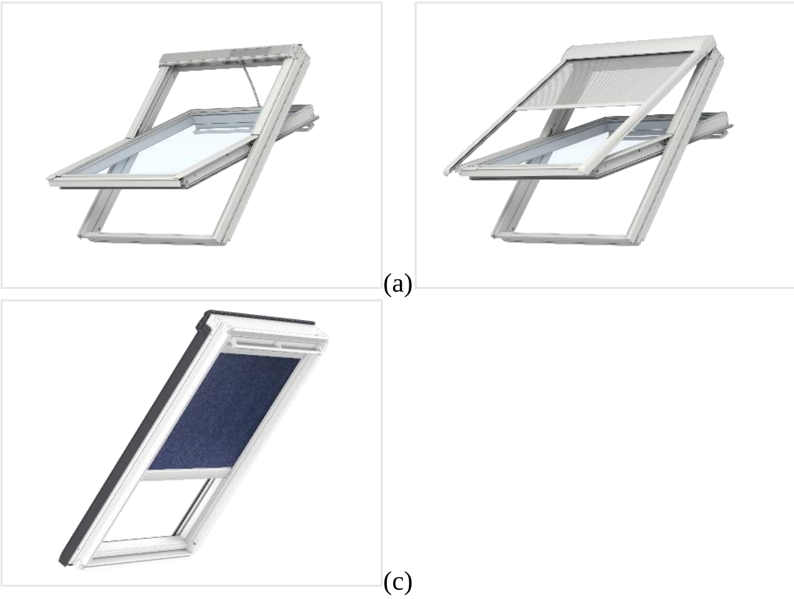

(b)

Figure 4-1 West side view of the a: examined case and b: floor plan of the upper floor (104: p.37).

The building was renovated in various steps (104). In 2006, the ground floor (over the basement) and the external walls (foam inside the bricks) were insulated and heating system (gas) was installed (104). The total rebuilt of the roof was started in 2013 and finished in 2014, with new wooden floor with insulation, roof insulation (mineral wool) and vapor barriers (Figure 4-2), and installation of eleven pivot roof windows (nine with motors and electrically driven actuators, Figures 4-3 (a-c); 104). The roof windows were installed in the bathroom (1), the three bedrooms (6), and the stairway corridor (2; 104). The roof windows (apart from those in the corridor) have integrated automated external shading systems (South orientation) and internal blackout blinds (Figures 4-3 (b, c); 104). Façade windows are wooden with double glazing (side-hung; 104). There is a small balcony on the South facing façade (Figure 4-1a; 104). Façade windows integrate light-white curtains, rollers, and venetian blinds (Figure 4-1a; 104). The doors are also wooden. Table 1-Appendix III presents the thermal characteristics of the envelope after the renovation, and Tables 2 and 3-Appendix III show the window-to-wall ratio for all the orientations and the window-to-net floor area for all the monitored rooms of the case study (104).

Figure 4-2 Renovation of the external wall and roof of the case stuydy.

Balanced mechanical ventilation system, temperature controlled, with heat recovery (maximum 86%) is installed also in the house (104). The maximum airflow rate is approximately 0.9 ach. The mechanical ventilation system was deactivated during the summer of 2016 (104). The opening and the use of the shading systems of the façade windows is totally manual (104). For 2016, these elements (manually controlled) were “out-of-use” based on the suggestions of the research team (104). Roof windows control during the summer of 2015 was manual and supported by an electronically assisted system (104). The system was based on time schedules set by the users (purge ventilation every 15 minutes for 4 times per day and others; 104). The control of the motorized roof windows (window opening and shading system activation) for summer period of 2016 was totally automated (window system, section 4-4; 104). Rain sensors support the function of the window system, in case of strong rainfall (104).



(a) (b) (c)

Figure 4-3 Roof windows a: with actuators, b: external, and c: internal shading systems.

4.2. WEATHER CONDITIONS

Figure 4-4 presents the ambient temperature (per month and in total, ^{o}C), the wind speed (in total, m/s), the accumulated global radiation (horizontal, kWh/m^2), and the accumulated precipitation (mm) of the specific location for the examined periods (summer 2015 and 2016; 104). Apart from the outdoor temperature, the environmental parameters were monitored from the Danish Meteorological Institute in Sjælsmark (3.7 km from the house; 104).

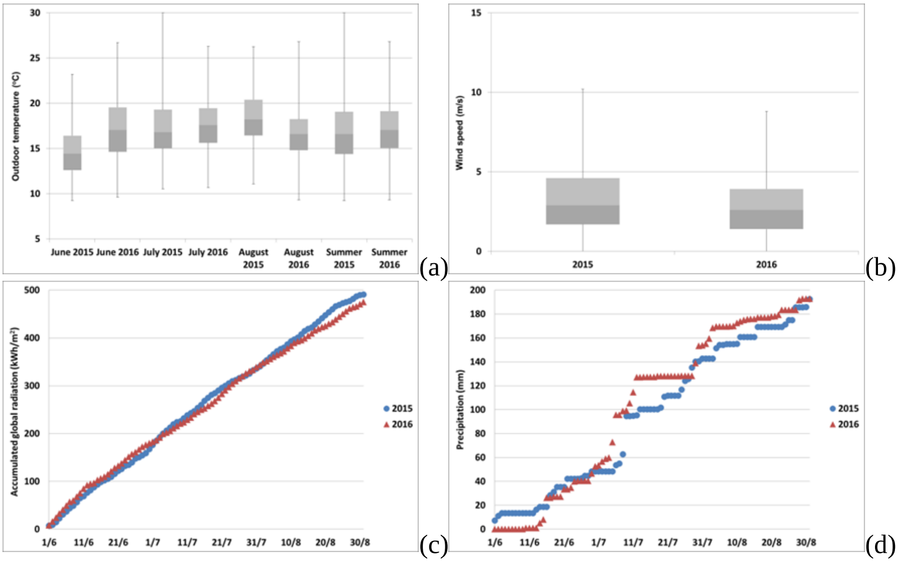


Figure 4-4 Ambient temperature (a; °C), b: wind speed intensity (m/s), c: accumulated horizontal global radiation (kWh/m^2), and d: precipitation (mm) of the examined location, during the examined periods (summer 2015 and 2016).

The peak outdoor temperature was in August 2016 and in July 2015 (Figure 4-4a). In terms of temperature, the summer of 2015 was slightly milder (June and July and on average) than the summer of 2016 (104). Wind speed intensity in 2015 was higher (peak and on average) than in 2016 (104). Accumulated global radiation lines almost coincide for the total of the examined periods (104). The differences are negligible (104). The raining hours for 2015 were 181 and 188 for 2016 (104). Ambient temperature and solar radiation affect the overheating incidents indoors (104). Wind speed and rainfall affect the window opening and the ventilation processes (104). Building occupants of the house experience identical weather conditions for both cooling periods (104).

4.3. MONITORING CAMPAIGN

The upper floor of the dwelling (Figure 4-1b) was monitored from 19 May 2015, and the rooms of the ground floor (living room and kitchen) were monitored from 18 May 2016 (104). For every examined room, the temperature (°C), the carbon dioxide concentration (ppm), and the relative humidity (%) have been continuously monitored with calibrated sensors encapsulated in silver plastic boxes (5-minute intervals), as well as the ambient temperature and relative humidity (externally; 104). The sensor was installed externally of the house totally protected from solar radiation under the extension of the roof eave (Figure 4-1a; 104). The sensors inside the dwelling were installed in places to avoid solar radiation and heat equipment or appliances, approximately in bed heights (104). Erroneous data was extracted from the weather files (104). Table 4-Appendix III presents the range and accuracy levels of the sensors for the environmental parameters (104).

4.4. WINDOW SYSTEM DESCRIPTION

The gateway (Figure 4-6) is connected with an embedded computer through a local area network (LAN) and with the window actuators through radio communication signals (104). The window system is accessed by a mobile application, developed specifically for this research study (104). The mobile application (Figures 4-7 (a-d)) is connected to the embedded computer (cloud service; 104). At the beginning of the project, a file was developed in JavaScript Object Notation format, which contains all the necessary information of the building (zones, windows, and other; 104). This file together with the monitored environmental parameters of the zones (and outdoors) is retrieved from the embedded computer at every time interval (10 minutes; 104). Algorithms repeated internally on a regular basis and are based on user decisions (104).

The window system has integrated three functions for user activation (104):

- Cooling (Ventilative cooling)
- Indoor air quality
- Shading

for the three occupancy states: non-occupied, occupied and night (104). Occupancy states change by the user or by schedule (morning and night time) and refer to a specific zone (104). The user decides which functions to activate for every occupancy state and zone (possible simultaneous activation, Figure 4-7b; 104). In addition, user sets the thresholds for 4 environmental parameters and the time interval of the algorithm (Figure 4-7a; 104):

- Indoor natural ventilation cooling temperature. Set point range: 18-30^{o}C
- Indoor temperature for shading. Set point range: ±3^{o}C relative to indoor natural ventilation cooling temperature
- Carbon dioxide. Set point range: 400-2000ppm
- Relative humidity. Set point range: 50-90%
- Time interval for control action. Range: never, 10 minutes-4 hours

In addition, users have the possibility to check the environmental parameters of the current day for every zone separately (Figure 4-7c; 104). Special signals for out of the limits environmental values show up for informative reasons (Figure 4-7d; 104). Users have the possibility to override (increase, decrease, close or open) or to deactivate the window system at any time during the day (time interval; 104). The three functions of the window system are presented below (Figures 4-6 (a, b); 104):

- Cooling function

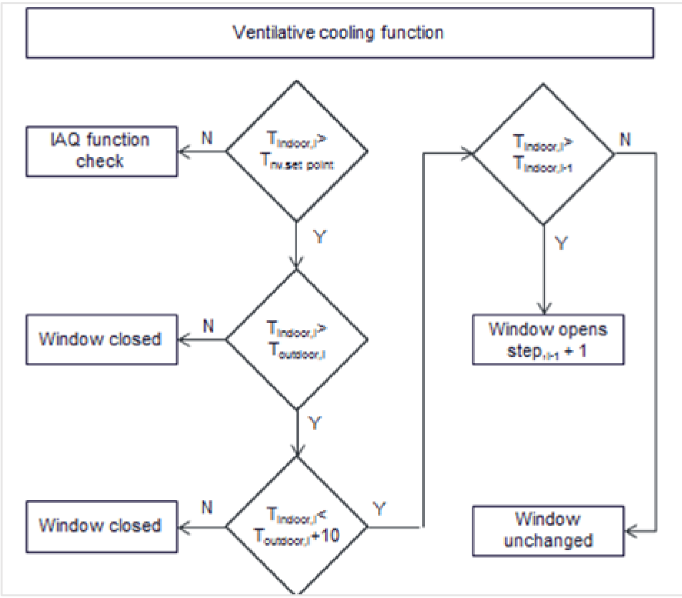
Connected windows of the zone open when the outdoor temperature is lower than the indoor operative zone temperature and when the indoor zone temperature is over the indoor natural ventilation cooling temperature set point, incrementally (10%/25%/50%/75%/100% of the window actuator; 104). After a time interval and if the indoor zone temperature is higher than the previous value, windows step to the next increment (if not, windows stay unchanged; 104). The maximum allowed temperature difference between indoor and outdoor is 10°C (draft reasons; 104).

- Indoor air quality function

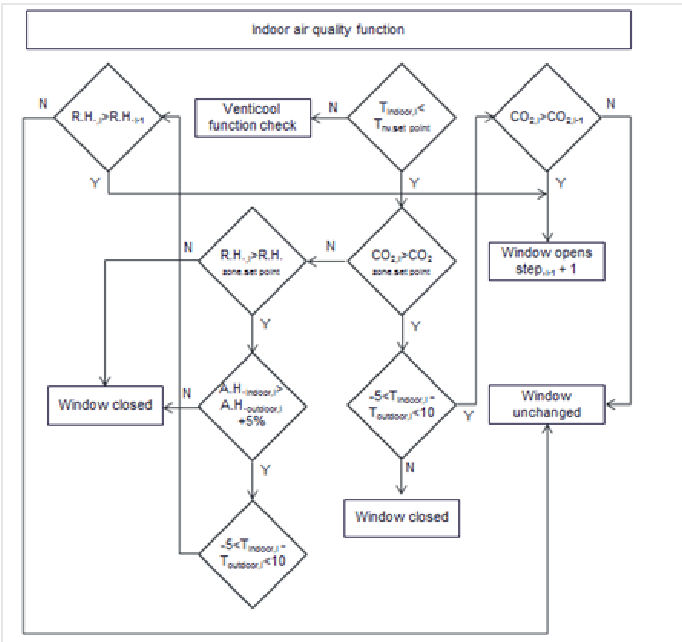
Connected windows of the zone open when the carbon dioxide concentration (ppm) or the relative humidity (%) is over the set point (also outdoor absolute humidity plus an error factor is lower than the indoor), incrementally (10%/25%/50%/75%/100% of the window actuator; 104). Between the two environmental parameters, carbon dioxide concentration is prioritized as the most important factor for window opening (indoor air quality function; 104). The maximum accepted temperature difference between indoor and outdoor temperature is 10°C and 5°C for colder and hotter outdoor conditions respectively (104). For parallel use of indoor air quality and cooling functions, the algorithm prioritized the cooling function for indoor operative temperatures over the indoor natural ventilation cooling temperature set point and the indoor air quality function for indoor operative temperatures below this set point (104).

- Shading function

The connected shading system, internal or external, is fully activated (open-close function) when the indoor operative temperature is over the shading temperature set point and the solar radiation affects the specific window (over 10° solar height and ±60° solar azimuth compared with the window orientation; 104).



(a)



(b)

Figure 4-5 Algorithms for a: ventilative cooling and b: indoor air quality function of the window system. (T: operative temperature (°C), $T_{nv.set\ point}$: indoor natural ventilation cooling temperature set point (°C), CO_2: carbon dioxide concentration (ppm), R.H.: relative humidity (%), A.H.: absolute humidity, and i: step i, Y: yes and N: no; 104: p.40).

Figure 4-6 Gateway of the window system (Visility ApS).

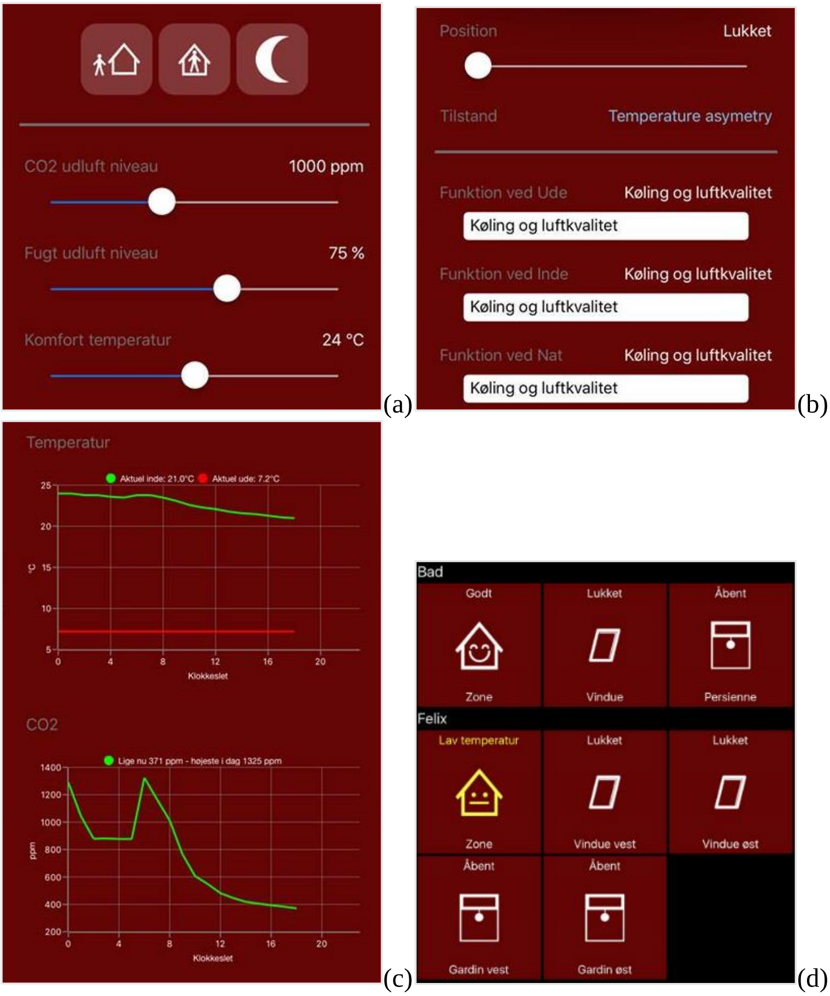


Figure 4-7 Screenshots of the developed mobile application of the window system a: user set points of the environmental parameters, b: activated functions for every occupancy state, c: monitoring of the environmental parameters of the current day, and d: general overview of the application (Visility ApS).

4.5. THERMAL COMFORT AND INDOOR AIR QUALITY ASSESSMENT

The thermal comfort assessment of the indoor environment for the 2015 and 2016 summer periods of the dwelling includes two metrics (dynamic and static) and criteria (section 1.2.1). The first one is the POR index (Categories I and II; 28) and the second one is the exceedance index with two static benchmarks, 27°C and 28°C (12, 104). Figures 4-8 (a-d) present the percentage of hours (%), from June to August, with thermal discomfort (overheating and undercooling) for all the rooms of the upper floor (2015 and 2016) and living room and kitchen of ground floor (2016) for both Categories I and II (104). Four out of five rooms of the upper floor presented overheating incidents in summer 2015, assessed with the criteria of Category II (Figure 4-8a; 104). The highest values of the index (over 3%) are presented for the main bedroom and the daughter’s room (104). These rooms are located at the Southern orientation and have high number of openings (104). The undercooling incidents were insignificant (104). The thermal discomfort of the upper floor in total, only overheating incidents, was less than 2% (104). All the rooms and floor in total managed to fulfill the requirement of the comfort Standard (5%; 25, 104). Thermal comfort assessment based on Category I for 2015 (Figure 4-8b) indicates that all the monitored rooms have both overheating and undercooling incidents with values higher than 5% (104). All the examined spaces did not fulfill the requirement of the comfort Standard (25, 104). The main bedroom and the daughter’s room present the highest thermal discomfort (104). The thermal discomfort of the floor in total is close to 6% (104). In terms of thermal comfort, the floor in total assessed as Category II for 2015 (28, 104). Overheating incidents for the examined bedrooms are possible in all the calculated running mean outdoor temperatures (Category I) and over 16°C for Category II (104). Undercooling incidents are significant mainly between 13.5°C and 18.5°C (Category I, all examined bedrooms; 104). Overheating is possible in lower than 27°C indoor operative temperatures (main bedroom, Categories I and II; 104).

For summer 2016, there is almost no overheating incidents (apart from living room) in all the examined rooms (Category II, Figure 4-8c; 104). Undercooling (under 3%) is the only thermal discomfort for this period (104). The most discomfort spaces are the son’s room and the main bedroom, around 2% (104). Floor thermal discomfort is 0.3% (only undercooling incidents).

Thermal comfort assessment for 2016 (Figure 4-8d, Category I) indicates that four out of seven examined rooms have overheating and undercooling incidents (104). Rooms with only undercooling incidents oriented to the North (Figure 4-1b; 104). In addition, four out of seven of the examined rooms have values higher than 5% (25, 104). The most discomfort rooms are the corridor (only undercooling incidents) and the main bedroom (higher than 10%; 104). The overheating is insignificant (less than 1%; 104). The corridor and son’s room show higher values compared with 2015 (undercooling incidents instead of overheating; 104). In total, floor and house in terms of thermal comfort belong to Category I (25, 104). For 2016, the thermal comfort hierarchy of the examined rooms is not identical for both Categories, as it is for 2015 (104).

For the ground floor, the living room fulfills the requirements of Category I and the kitchen the requirements of Category II (only undercooling; 104). These spaces were not monitored during 2015 for comparison of the outputs (104). The living room has similar discomfort incidents in comparison with the daughter's bedroom of the upper floor (similar orientation; 104). On one hand, the living room has more heat gains compared to the daughter's room, but on the other hand, the living room has significant thermal mass (walls) for heat storage and shaded more during the day (104).

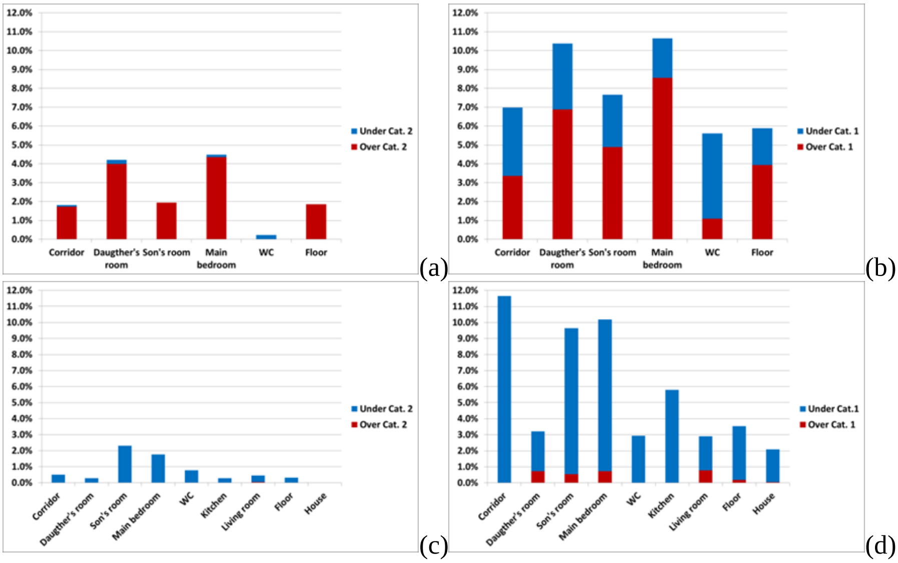


Figure 4-8 Thermal discomfort assessment (adaptive method, %) in room, floor, and house level of the dwelling for summer of 2015 (a, b) and 2016 (c, d), and Categories I (b, d) and II (a, c; 104: p.41).

For bedrooms, there is overheating in running mean outdoor temperatures over 18°C (Category I) and indoor operative temperature over 26°C (Category I; 104). Undercooling incidents show up in all calculated running mean outdoor temperature values (both Categories; 104). Figure 4-9 highlights the overheating incidents (number of hours, both metrics and criteria) for the three bedrooms of the dwelling during night time (23:00-07:00) for both periods (2015 and 2016; 104). The overheating incidents during night for 2016 are insignificant (104).

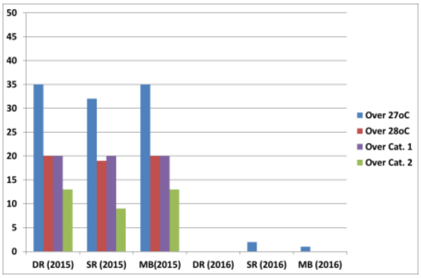
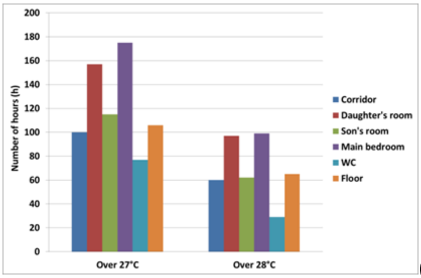


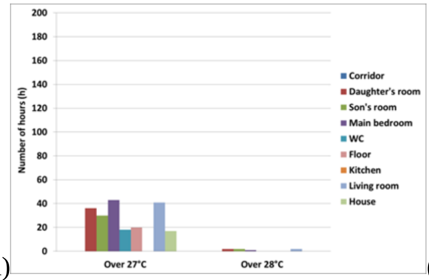
Figure 4-9 Number of hours (h) with overheating incidents, assessed by both metrics and criteria, for the three examined bedrooms (DR: daughter's room, SR: son's room, and MB: main bedroom) for 2015 and 2016 at night (23:00-07:00; 104: p.41).

All the examined rooms present lower operative temperatures on average (also peak values) in 2016 compared with 2015 (apart from W.C.; 104). The maximum indoor operative temperature for 2015 is presented in the main bedroom (31.6^{o}C) and for 2016 in all 3 bedrooms (28.1^{o}C; 104). The minimum indoor operative temperature for 2015 is presented in the corridor (19.0^{o}C) and for 2016 in the son's room (18.7^{o}C; 104). Most of the examined rooms have lower minimum indoor operative temperature in 2016 compared with 2015 (104).

Figures 4-10 (a, b) show that thresholds (27^{o}C and 28^{o}C) are exceeded for more than 100 and 25 hours respectively for all three bedrooms in 2015 (12, 104). The corridor has exactly 100 hours over 27^{o}C in 2015 (12, 104). The second requirement (maximum 25 hours above 28^{o}C) is not fulfilled in any room of upper floor for 2015 (104). For 2016, all rooms of the upper and ground floors fulfill both thresholds and fulfill the requirements of the regulation (Figure 4-10b; 104). The highest overheating incidents are in the main bedroom and daughter's room (upper floor), for both years (assessed by 27^{o}C threshold; 104). The living room also shows high overheating incidents (2016; 104). For 2016, the corridor and kitchen (North oriented, Figure 4-1b) show no overheating incidents (assessed by 27^{o}C threshold; 104). The incidents, assessed by 28^{o}C threshold, for 2016 are insignificant (104). The hierarchy of the bedrooms in terms of overheating is similar for both thresholds in 2015 (104). The upper floor, in total, does not fulfill the requirements of the regulation for 2015: 106 and 65 hours respectively (104). Overheating incidents, in floor and house level, for 2016 are 20 and 17 respectively (assessed by 27^{o}C threshold; 104). No hours over 28^{o}C are calculated, in floor and house level, respectively (Figure 4-10b; 104).

Static and dynamic performance indicators and metrics cannot be compared directly because they assess different discomfort conditions (104). The static metric fails to highlight the undercooling risk that exists in many rooms during the peak summer period (104). Both metrics highlight the rooms with the highest overheating risk (104). The undercooling risk in bedrooms during hot summer periods (night) has to be investigated in the future.



(a)


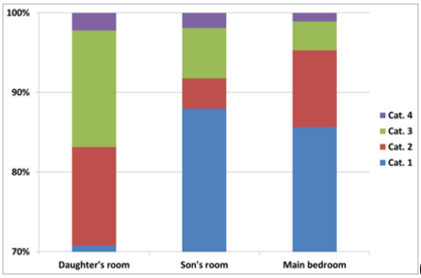
(b)

Figure 4-10 Number of hours (h) over 27°C and 28°C for all the examined rooms for a: 2015 and b: 2016 (104: p.45).

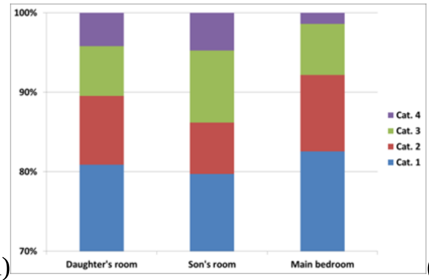
Indoor air quality is assessed (carbon dioxide and relative humidity, Table 6-Appendix III) for every examined room based on comfort Standards (static thresholds) and national Danish regulations (28, 104, 114). The Danish Building Institute also suggests maximum acceptable relative humidity of the indoor spaces: less than 1% of the time over 75% relative humidity (114). In general, thresholds of comfort Standards are not applicable to residential buildings (indoor air quality; 28, 104).

As far as the carbon dioxide concentrations are concerned, all the bedrooms do not fulfill the requirements of Category II, apart from the main bedroom (2015, Figure 4-11a; 104). In 2016, the daughter's room has slightly better indoor environment, compared with 2015 (Category I and II, Figure 4-11b; 104). The opposite condition is assessed for the son's room (104). The indoor environment in the main bedroom is comparable for both periods (104).

As far as the relative humidity is concerned, all the bedrooms do not fulfill the requirements of Category II (both years; 104). In addition, all rooms, W.C. included, fulfill the requirement of the national regulation for both periods (104, 114). The maximum value for relative humidity for 2015 is 82% and for 2016 is 78% (104). Window system effectiveness, in terms of air quality, during peak summer period is straight comparable with small deviations to the performance of the combined use of the mechanical ventilation system and the manual use of the façade and roof windows (104).



(a)



(b)

Figure 4-11 Indoor air quality assessment (carbon dioxide (ppm), Categories I, II, III, and IV) for the three examined bedrooms, for summer a: 2015 and b: 2016 (104: p.45).

4.6. OCCUPANCY BEHAVIOR ON WINDOW SYSTEMS

Table 4-1 presents the user set points of the window system for all the examined rooms during summer 2016 (104). The set points were constant and did not differentiate significantly with the outdoor conditions (104). Occupants tried to solve local thermal, air quality and glare problems with manual overrides of the window system (104). Time intervals for control actions were from 10 minutes to 1 hour, but mainly 30 minutes (104).

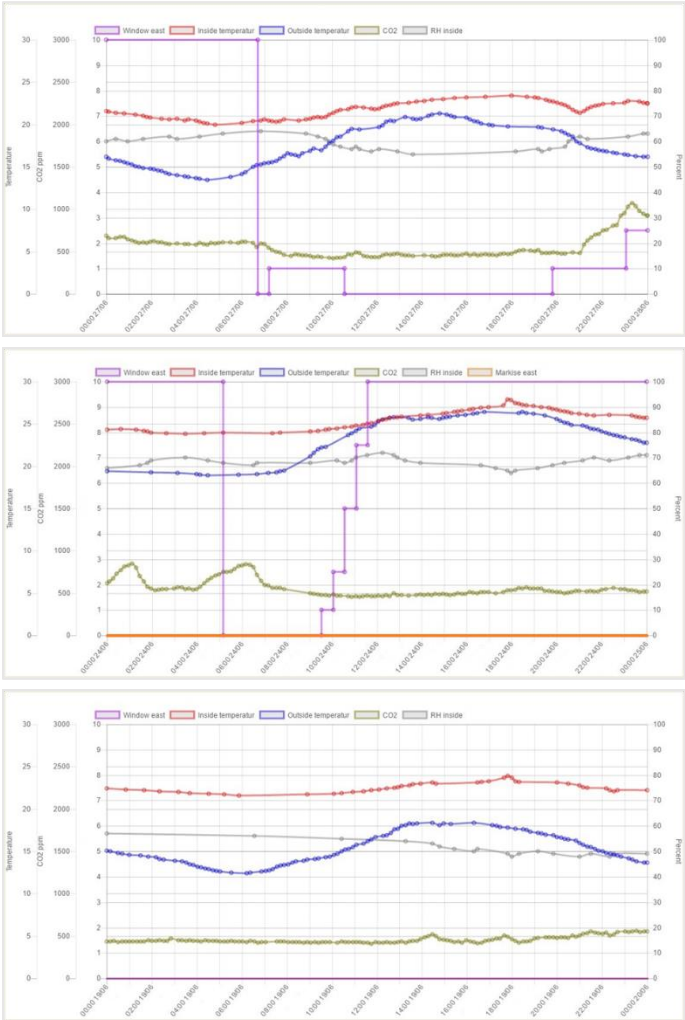
Table 4-1 User set points of the environmental parameters of the window system, for different rooms (summer 2016; 104: p.42).

	Corridor	**Daughter's room**	**Son's room**	**Main bedroom**	**W.C.**
Indoor natural ventilation cooling temperature (°C)	24 (June: 22)	24	24 (June: 23)	24	24
Indoor temperature for shading (°C)	-	0÷2	0÷2	-3÷2	-
Carbon dioxide (ppm)	1000	1000	1000	800	1000
Relative humidity (%)	60	60	60	60 (June: 50)	60-70

The monthly mean comfort temperatures were 24.6°C for June, 24.7°C for July and 24.2°C for August (section 1.2.1; 104). These temperatures were higher than the used indoor natural ventilation cooling set point (24°C maximum) for every room (Table 4-1; 104). This action indicates that occupants in bedrooms in heating dominated temperate climates feel more comfortable with temperatures lower than those proposed by the comfort Standards (28, 104). Undercooling incidents were not a reported issue from any occupant of the house during summer 2016 (104). A number of undercooling incidents for the corridor and the son's room were monitored in June when the set points for ventilative cooling were minimum (22°C and 23°C respectively, Table 4-1; 104). The main bedroom also had comparable minimum set points for indoor air quality function (carbon dioxide concentration during all period and relative humidity in June; 104). Occupants of two out of three bedrooms (apart from son's room) deactivated the window system during night because of noise nuisance from the actuator (104). Instead, the users were used to set a fixed window opening percentage, sometimes also 100%, for the whole night period (Figures 4-12 (a, b); 104). This action resulted also in a number of undercooling incidents (9 hours outside the limits of Category II and 14 hours outside the limits of Category I, Figure 4-12a; 104). Minimum windows opening percentages for indoor air quality reasons are suggested for summer nights with low outdoor conditions, e.g. maximum 10°C difference between indoor and outdoor temperatures (104). The non-automated use of the windows during night occasionally affects the indoor air quality of the bedrooms (humid environment) and causes unnecessary operation of the system the next couple of days (Figure 4-12a; 104). In general, thresholds proposed for relative humidity assessment are not applicable, by definition, to residential buildings (28, 104). The relative humidity control of the indoor air quality function of the window system suggested to be active only on specific rooms with severe violations (104). A different user time interval for the indoor air quality function (smaller) on one hand helps the thermal optimization of the space, but on the other hand increases the complexity of the system (104). The morning and night set points of the occupancy states varied considerably during the total examined period for all the examined rooms (104).

The activation of the external shading system (manual override) during daytime would decrease the overheating risk to the minimum (Figure 4-13b). The deactivation of the shading systems is a common process for these climatic conditions (visual contact with the outdoor environment; 104). Typically, the shading systems are used in bedrooms to avoid the early morning sun (104).

The window system is active only when it is absolutely necessary to improve the indoor environment of the dwelling with minimum energy use for the motors (Figure 4-12c; 104). The energy use of the mechanical ventilation systems for this period (June to August 2015) would be approximately 220.8 kWh (for typical air change rates). The energy use of the window system for the same period (2016) was 10.1 kWh (95.4% energy savings). The energy savings from the deactivation of the mechanical ventilation system add extra value to the performance of the window system (104). The use of the window system may be extended also during the transition months and heating season (104).



(a)

(b)

(c)

Figure 4-12 Daily indoor environment (temperature: °C, carbon dioxide concentration: ppm, and relative humidity: %) and use of windows and shading systems (%) for different rooms (a: main bedroom, b-c: daughter's room, Visility ApS; 104: p.43).

4.7. SIMULATION OF THE WINDOW SYSTEM

Literature review indicates that there are no mature and validated BPS engines which could accurately simulate advanced and complex natural ventilation and ventilative cooling control strategies (32, 70). Controls improve method and strategy effectiveness considerably and, as a result, the control representation in BPS engines needs to accurately reflect how real algorithms are developed (96). This section presents the methodology and framework of how to simulate the basic core ventilative cooling algorithm (step-approach) of the developed window system on time-step coupled BPS environments (section 4.4; 20, 104). For the realistic simulation of the integrated algorithm, the ESP-r software is time-step coupled, in a virtual environment, with Building Controls Virtual Test Bed (BCVTB) engine (20). In addition, a numerical analysis has been conducted to examine specific operational functions (control approaches) used in the window system (20, 104). These functions are related mainly with the nature (dynamic or static) of the indoor natural ventilation cooling set point and the number of steps of window opening (step-approach, section 4.4; 20, 104). The window system uses a 5-step approach and static (fixed values) indoor natural ventilation cooling set points (section 4.4; 20, 104). The outputs of this numerical analysis will be directly applicable to the research for the further improvement of the window system (20, 104). This numerical analysis uses the calibrated case study model of section 4.1 (20, 104). Similar metrics (POR index (Category I and II) and exceedance threshold (27^{o}C and 28^{o}C)) are used to perform thermal discomfort assessment for the examined period of the analysis (summer 2016, section 4.5; 20, 104). The calibration process is highlighted as the initial part of the proposed workflow for the documentation of the effectiveness of the ventilative cooling algorithm of the developed window system (or any other window system; 20).

4.7.1. SOFTWARE COUPLING

Dynamic thermal building response and complex airflow phenomena are precisely simulated and represented in ESP-r engine (20, 115-117). BCVTB works as an emulator platform (middleware) for external control of flow network components (20). An analytical description of ESP-r and its standard and extended capabilities are presented in (20, 68, 116-119) and similarly for BCVTB are presented in (20, 68, 120, 121).

The coupling of the two engines allows the transfer of an array of values between the model and the controller at the beginning of each time step k (measured states, x(k), and measured disturbances $u_d(k)$, Figure 4-13; 20). The input data is either parameters (constant) or variables (20). The measured states array integrates the zones indoor operative temperatures (Figure 4-13; 20). The measured disturbance is the ambient temperature (Figure 4-13; 20). The arrays of states represent the sensor outputs that act as input values for the window system (section 4.4; 20). BCVTB controller, based on the control logic (Figure 2-Appendix IV), returns an array of opening percentages $u_c(k)$ for all the windows (roof windows for this case study) of every zone (20). Current time is also exchanged (20). For this coupling, the time interval is considered to be equal to half an hour (20). The developed control algorithm is active during all day for the whole examined period (summer 2016; 20).

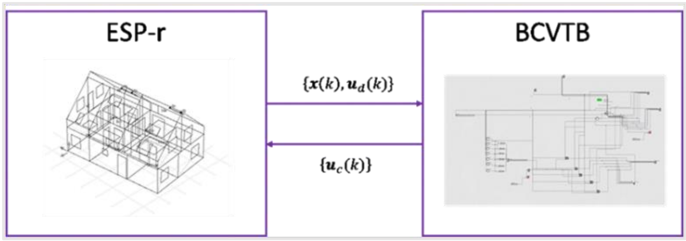


Figure 4-13 Communication architecture (measured state-disturbance state and window opening) of the coupled tools (ESP-r and BCVTB; 20).

4.7.2. RESULTS

The case study (section 4.1) is modeled as a free-floating building (no mechanical ventilation and active systems) in ESP-r, with a detailed AFN (indoors and outdoors) according to its design specifications (summer 2016; 20, 104). The specifications of the model (building characteristics, weather data, and others) and simulation assumptions (as far as the occupancy and internal heat gains profiles and others) are described analytically in (20, 104). The only simulated active system is the developed window system (all day, façade windows and shading systems deactivation; 20).

The model is calibrated using monitored data acquired between 13-18 June 2016 (section 4.2; 20). During this period, the house was not occupied (20). Three criteria are used in this research study for the verification of the agreement between the two datasets (simulated and monitored) for all the examined rooms of the house (bedrooms, W.C. and corridor; 20, 122, 123):

- Visual observation.
- Magnitude-fit metric or the absolute average temperature difference between the datasets. Results less than 1.00°C are classed as "acceptable".
- Shape-fit metric or Spearman's rank correlation coefficient (shape correspondence). Results more than 0.80 are classed as "acceptable".

Figures 4-14 (a-c) present the comparison of the data series for three reference rooms of the case study (20). The visual observation shows adequate agreement between the datasets (20). Table 4-2 presents the examined metrics for all the rooms (fulfillment of the requirements; 20).

Table 4-2 Shape-fit and magnitude-fit metrics for all the simulated rooms of the case study for the total of the examined period (20).

Metrics	**Main bedroom**	**Son's room**	**Daughter's room**	**Corridor**	**W.C.**
Spearman's coefficient, (>0.80)	0.92	0.85	0.92	0.92	0.95
Absolute average temperature difference (°C), (<1.00)	0.30	0.60	0.50	0.30	0.60

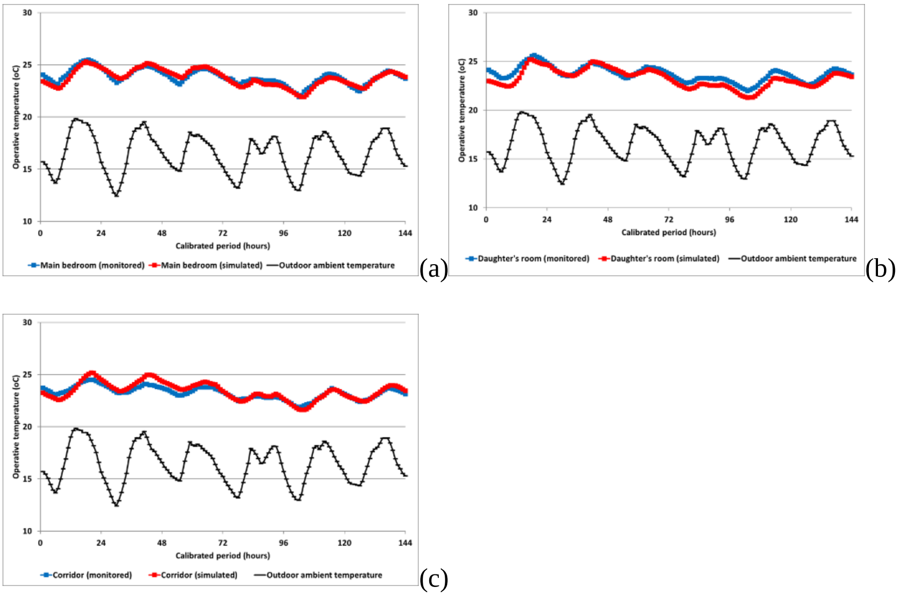


Figure 4-14 Monitored and simulated indoor operative temperature (°C) and ambient temperature (°C) datasets for the examined period and for different rooms of the upper floor (a: main bedroom, b: daughter's room, and c: corridor; 20).

One control approach has three opening steps for the actuator until the full opening of the roof windows (25%/50%/100%; Figure 4-5a) and the second approach has five opening steps (10%/25%/50%/75%/100%; 20). The advantage of the 3-step approach is that the ventilative cooling control strategy has higher performance, because the roof windows of the examined zones open faster (3-time step intervals; 20). The advantage of the 5-step approach is that the ventilation is more controllable and, as a result, the indoor space faces fewer issues from undercooling incidents, draft, and high internal air velocities (20).

Figures 4-15 (a-d) present the percentage difference (delta %, refer to summer 2016) of the thermal discomfort and overheating for different number of opening steps (5-step and 3-step), indoor natural ventilation cooling set points (22ºC-26ºC), assessment metrics (dynamic and static metrics and four criteria; section 4.5) and examined rooms (20). The outputs indicate that, in terms of overheating and thermal discomfort, the effectiveness of the window system for these climatic conditions is not affected (less than 1%) by the number of steps of the actuator until the full opening of the windows (3 or 5) at the control algorithm for low and medium indoor natural ventilation cooling set points (22ºC-24ºC, four criteria; 20). For higher set points, the differences are more discrete for all the rooms and metrics (20).

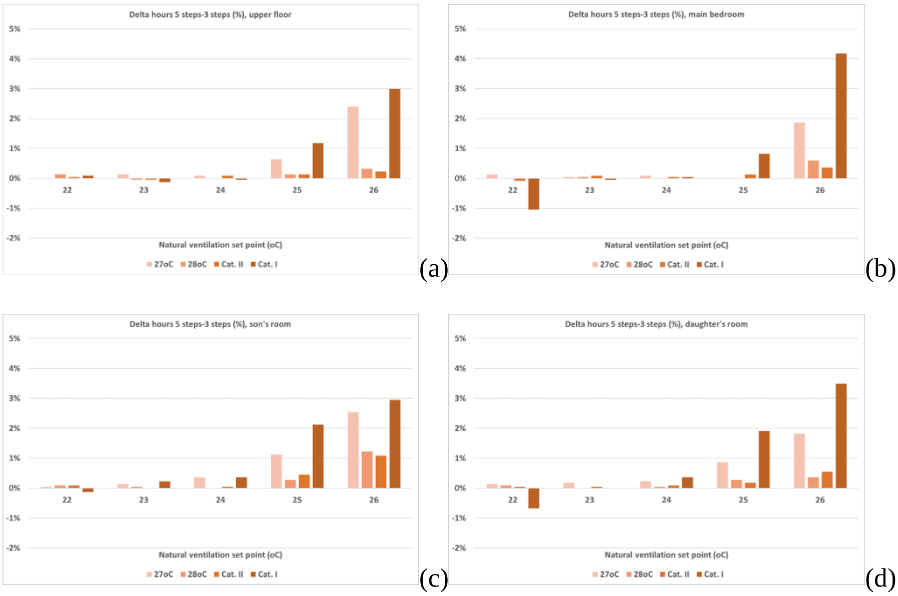


Figure 4-15 Percentage difference-delta (5-step minus 3-step approach; %) of thermal discomfort and overheating for different rooms (a: upper floor on average, b: main bedroom, c: son's room, and d: daughter's room), during the examined summer period, and for different assessment metrics and criteria and indoor natural ventilation cooling set points (20).

The determination of the optimum indoor natural ventilation cooling set point is necessary for the maximum effectiveness of the window system and the thermal and energy optimization of the space (20). Two different control approaches are investigated for the determination of the optimum indoor natural ventilation cooling set point for actuating the roof windows (20). The first one is based on static values

(22°C-26°C, constant during the examined period) of operative temperature and the second one on dynamically changing values based on the dynamic adaptive theory (comfort temperature ±2°C, equation 1-2; 20). The advantage of the former approach is that the window system user is responsible for the set point values and has a personal feeling about them (20). The latter approach makes the window system even more automated (20). The window system follows the 5-step approach as described in section 4.4 (time interval half an hour; 20). The outputs of the analysis indicate that the static indoor natural ventilation cooling set points perform better (best results with 22°C and 23°C) than the dynamic for all the examined rooms, assessing metrics (dynamic and static), and criteria (Table 8-Appendix IV; 20).

4.8. CONCLUSIONS

The chapter of this research study presents a new developed automated window opening control system with integrated heuristic passive cooling control strategies and highlights ability of the system to maintain or improve the indoor environment, in terms of overheating and air quality, of a deep energy renovated typical single-family dwelling in Northern temperate climatic conditions, during the peak cooling season (104). The indoor thermal and air quality assessment of the case study illustrates the fact that active and passive ventilation components and shading systems, if manually controlled, cannot assure indoor environmental conditions inside the national regulation and comfort Standards limits and without major violations (104). In contrast, the use of automated window opening control system, like the one developed for this research study, may significantly diminish the indoor discomfort assessed by static and dynamic metrics in all rooms without any significant compromise of the indoor air quality (104). For this case study, the window system controls only a small part of the available air flow components of the house (roof windows; 104). The low energy use of the window systems and the total energy savings, more than 95%, from the deactivation of the mechanical ventilation system strengthen and enhance the possibility of use of these systems in the future. The description of the architecture of the components and control strategies and the identified limitation and suggestions after the monitoring campaign of the window system may be used as a baseline for the development of window systems applicable to other climatic conditions and building types (104). The suggested optimum set points may be used as reference targets for installed automated window opening control systems with similar functions and control strategies in Northern temperate climates (104).

Static metrics imposed by national regulations fail to identify all the possible thermal discomfort problems, which arise during peak cooling periods (104). These problems are related mainly with overheating incidents on lower indoor (and outdoor) temperatures and undercooling risk (104).

Finally, this research study presents a simulation process of the major ventilative cooling function of the window system on coupled BPS environments through a well-defined proposed framework and workflow (20). Under this framework, the simulation and representation of any other developed window system or more sophisticated ventilative cooling control strategy is possible (20). Through this simulation process, the two fundamental control approaches of the developed window system have been documented numerically (20).

For further information, please refer to Articles 3-Appendix III and 4-Appendix IV: "Automated roof window control system to address overheating on renovated houses: Summertime assessment and intercomparison." and "Ventilative cooling through automated window control systems to address thermal discomfort risk during the summer period: Framework, simulation and parametric analysis."

CHAPTER 5. COMPARISON AND STATISTICAL ANALYSIS OF OVERHEATING METRICS

Researchers and building designers apply and use different long-term overheating indices, because they follow different thermal comfort theories, models, national regulations, and comfort Standards (31). As a result, there is no common scientific ground for generalization and criticism of their outputs and conclusions (31). Thermal discomfort metrics are widely used in the scientific literature for optimization purposes and for thermal comfort assessment of simulated case studies or existing buildings (29, 31). Without undercooling incidents, the metrics calculate only overheating risk (31). Quantitative and numerical relation and correlation of metrics would decrease the analysis being conducted during the design and operational phase of new or existing buildings (31). This chapter summarizes and statistically analyzes the numerical analysis of chapters 2 and 3. This analysis is extended further with the calculation and presentation of the outputs of four additional overheating metrics (section 1.2.1.) for the same case studies, energy renovation measures and passive cooling strategies. The used metrics are as follows:

- Percentage of hours outside the comfort range (Category II)
- Percentage of hours over fixed temperature thresholds (25^{o}C (occupied hours and all day), 26^{o}C and 28^{o}C (occupied hours))
- Degree hours outside the comfort range (Category II)
- Difference between peak indoor and annual average outdoor temperature

The analysis, 66 variants, extends findings of previous research works by comparing and correlating metric outputs, which refer to different building geometries in different climatic conditions (Austria, Denmark, South France and U.K.; 31, 35).

5.1. STATISTICAL ANALYSIS

The statistical linear regression analysis is carried out with the use of the tool "R package" version 3.2.4 (124). Table 5-1 presents the minimum and maximum values, the central tendency (mean and median), the standard deviation, and the dispersion (coefficient of variation) of all variants and metrics for the total of the statistical analysis (31). Adjusted coefficients of determination (1st-order and 2nd-order polynomial and logarithmic models; R^2) are calculated (Table 5-2; 31):

- With categorization of the variants based on their origin (country, climate, geometry; Austria, Denmark, South France, and the U.K.)

- Without categorization of their variants

Tables 5-2 presents the adjusted coefficients of determination for all pairs for the total of the statistical analysis (with and without categorization; 31). The "best-fit" models between dynamic (POR and DHRS) and static metrics are all 2nd-order polynomial equations (with categorization, Table 5-3, Figures 5-1 (a-d); 31). The calculated models are parametric (different points of interception) for the four different cases (Table 5-3; 31). For these pairs of metrics, the coefficients are considerably higher with the categorization process for similar regression analyses (Table 5-2; 31). The coefficients range from 0.84 to 0.99 (31). The higher the threshold is (e.g. 28^{o}C), the higher the coefficient is for both examined dynamic indices (31). Coefficients are higher for POR index compared with the DHRS index for the same analyses (31). The South French case study presents the lowest coefficients (3 out of 4, Figures 5-1 (a-c)).

Table 5-1 Univariate analysis of the metrics for all the variants (F_25_A: 25^{o}C threshold all day, F_25_O: 25^{o}C threshold occupied hours, F_26: 26^{o}C threshold occupied hours, and F_28: 28^{o}C threshold occupied hours; 31: p.9).

Index	**Minimum**	**Maximum**	**Mean**	**Median**	**Standard deviation**	**Coefficient of variation**
POR	0.0	36.0	12.1	10.2	10.0	0.8
DHRS	0.0	7447.0	1485.6	860.1	1617.5	1.1
F_25_A	8.0	43.4	25.5	25.6	10.5	0.4
F_25_O	8.7	44.1	25.7	26.2	10.5	0.4
F_26	5.1	39.7	21.2	20.4	10.6	0.5
F_28	0.2	35.0	12.6	9.1	9.2	0.7
DT	15.3	30.5	22.2	22.0	4.3	0.2

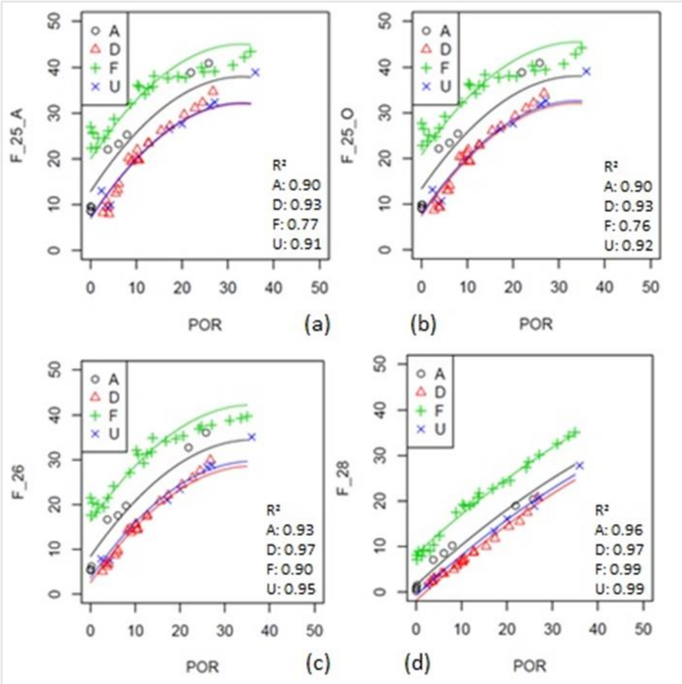


Figure 5-1 Best-fit models (with categorization) of the linear regression analyses of the POR index (x-%) with the static metrics (y-%; F_25_A: 25ºC threshold all day, F_25_O: 25ºC threshold occupied hours, F_26: 26ºC threshold occupied hours, and F_28: 28ºC threshold occupied hours) for all the variants (A: Austria, D: Denmark, F: South France, and U: U.K.; 31: p.7).

Table 5-2 Adjusted coefficients of determination (R^2) of the linear regression analyses (with (*) and without categorization) for all pairs of indices (31: p.9).

X	**Y**	**1st-order polynomial model**	**1st-order polynomial model***	**Logarithmic model**	**Logarithmic model***	**2nd-order polynomial model**	**2nd-order polynomial model***
POR	DHRS	0.87	0.90	0.57	0.73	0.91	0.96
POR	F_25_A	0.60	0.88	0.51	0.75	0.60	0.92
POR	F_25_O	0.59	0.89	0.50	0.77	0.59	0.92
POR	F_26	0.63	0.93	0.53	0.80	0.62	0.96
POR	F_28	0.75	0.99	0.62	0.84	0.74	0.99
POR	DT	0.04	0.95	0.05	0.96	0.14	0.95
DHRS	F_25_A	0.36	0.78	0.30	0.66	0.39	0.84
DHRS	F_25_O	0.35	0.79	0.29	0.68	0.38	0.85
DHRS	F_26	0.38	0.83	0.32	0.71	0.41	0.89
DHRS	F_28	0.51	0.90	0.40	0.74	0.53	0.95
DHRS	DT	0.12	0.94	0.13	0.94	0.19	0.96
F_25_A	F_25_O	1.00	1.00	0.96	0.96	1.00	1.00
F_25_A	F_26	0.99	0.99	0.97	0.97	0.99	1.00
F_25_A	F_28	0.88	0.89	0.93	0.95	0.95	0.96

F_25_A	DT	0.05	0.94	0.06	0.94	0.05	0.95
F_25_O	F_26	0.99	0.99	0.97	0.97	0.99	1.00
F_25_O	F_28	0.89	0.89	0.93	0.95	0.95	0.96
F_25_O	DT	0.07	0.94	0.07	0.94	0.06	0.94
F_26	F_28	0.93	0.94	0.92	0.95	0.97	0.98
F_26	DT	0.07	0.95	0.06	0.95	0.06	0.95
F_28	DT	0.03	0.95	0.03	0.96	0.02	0.96

Table 5-3 Coefficients of best-fit models of linear regression analyses (2nd-order polynomial) of dynamic with static indices (categorization, interception point based on the country; 31: p.10).

X-Y	**x_local**	**I(x_local^2)**	**Denmark**	**South France**	**U.K.**	**Austria**
POR-F_25_A	1.517	-0.023	-5.879	7.129	-5.71	12.860
POR-F_25_O	1.456	-0.021	-5.918	7.453	-5.43	13.330
POR-F_26	1.438	-0.020	-5.832	7.815	-4.80	8.396
POR-F_28	0.926	-0.005	-3.371	6.769	-2.23	1.521
DHRS-F_25_A	0.009	0.000	-6.804	8.526	-6.85	16.130
DHRS-F_25_O	0.009	0.000	-6.897	8.802	-6.60	16.470
DHRS-F_26	0.009	0.000	-7.122	9.130	-6.03	11.410
DHRS-F_28	0.008	0.000	-5.597	7.680	-3.87	3.419

Figure 5-2 presents the correlation (R^2: 0.91) of the POR and DHRS indices (without categorization; 31). With categorization, the coefficient does not increase considerably (0.96; 31). The correlation is higher for lower values (less than 15%) of POR index (31).

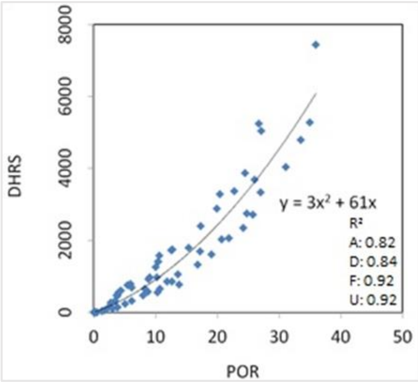


Figure 5-2 Best-fit model of the linear regression analysis of the POR index (x-%) with the DHRS index (y-ºCh, without categorization) for all the variants (A: Austria, D: Denmark, F: South France, and U: U.K.; 31: p.7).

The best-fit models between static indices (6 pairs) are mainly 2nd-order polynomial equations (31). The coefficients range from 0.95 to 1.00 (without categorization; 31). The coefficients are almost similar (0.96 to 1.00) when the categorization process is applied (31). Without categorization process and 1st-order linear regression analysis, the coefficients range from 0.88 to 1.00 (31). These equations are preferred over best-fit equations, for simplicity reasons, without significant accuracy penalty (Figure 5-3; 31).

The correlation of the DT index with the other indices show coefficients from 0.02 to 0.19 (without categorization) and from 0.94 to 0.96 (with categorization; 31). The reason for these results is that the index is highly related with the annual average outdoor temperature and climate, by definition (section 1.2.1; 31). The index remains almost constant (zero inclination) independently of the values of the other metrics (31).

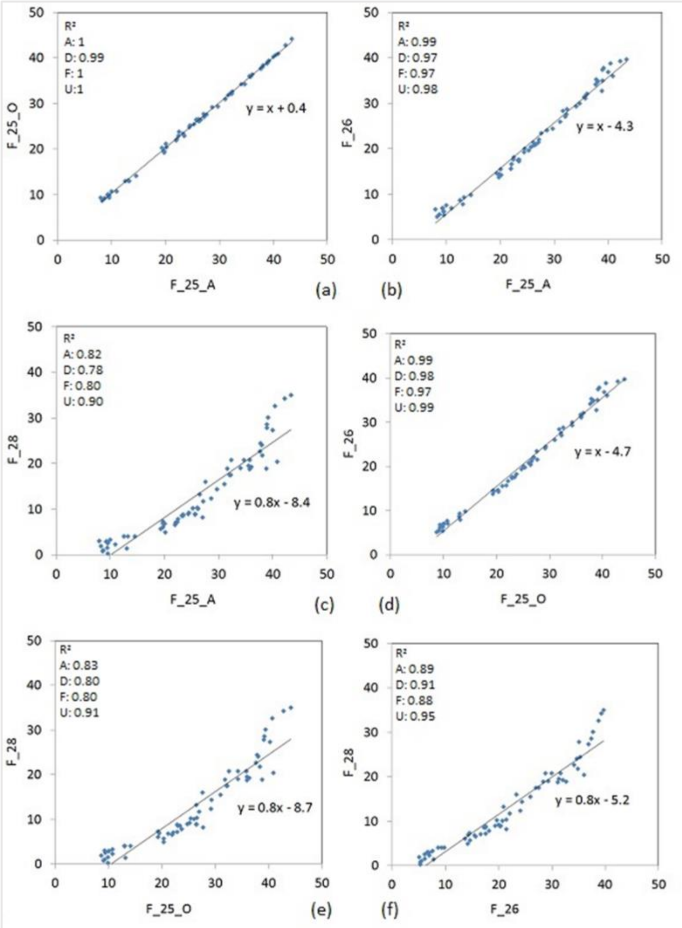


Figure 5-3 1^{st}-order polynomial models (without categorization) of the regression analyses of the static metrics with each other (x, y-%; F_25_A: 25^{o}C threshold all day, F_25_O: 25^{o}C threshold occupied hours, F_26: 26^{o}C threshold occupied hours, and F_28: 28^{o}C threshold occupied hours) for all the variants (A: Austria, D: Denmark, F: South France, and U: U.K.; 31: p.8).

5.2. CONCLUSIONS

The statistical analysis of this chapter indicates that it not possible to develop and suggest a general relationship (model) between both dynamic (POR and DHRS) and all the examined static metrics (31). However, for every examined case individually, this relationship is clear and distinguished, described by 2^{nd}-order polynomial equations (best-fit models; 31). National level relationships may be developed from stakeholders and local authorities based on different reference buildings, building types and updated or future climatic conditions (larger data set; 31). The dynamic indices have the scientific consensus and concord for thermal comfort assessment of naturally ventilated buildings (31). These metrics may be transformed to more simple metrics (static), totally understandable by the users and designers, different for every location or climatic condition (31). On the other hand, as described analytically in chapter 4, the static metrics fail to identify specific violations of the indoor thermal condition (undercooling; 104).

Dynamic metrics originate from the same adaptive theory highly correlated with each other, with high adjusted coefficient of determination (31). This correlation, also 2nd-order polynomial equation, is independent of the case studies, geometries, and climatic conditions (31). Use and inclusion of both metrics to the comfort Standards and comfort analyses is a hyperbole (31). Deviation limits suggested for the one index may be calculated also for the other index based on the suggested equations (31). The DT index statistically cannot be correlated with any other index (31).

Finally, the statistical analysis indicates that it is possible to develop and suggest relationships between static metrics for general use, independently of the building and climate (31). The relationships are linear with high adjusted coefficients of determination (31). Double overheating thresholds suggested by a number of national regulations and initiatives is again a hyperbole (31).

For further information, please refer to Article 2-Appendix II: "Comparison and statistical analysis of long-term overheating indices applied on energy renovated dwellings in temperate climates."

CHAPTER 6. CONCLUSIONS

The objectives of this research study are to investigate, highlight, and address the challenges related to decrease of the overheating risk (severity, intensity, likelihood, and duration) in energy renovated single-family houses under different European temperate climates as well as to develop a full concept (solution and control strategies) based on ventilative cooling and other secondary passive cooling methods (shading and others) for this type of buildings, avoiding additional energy use and discomfort violations. This chapter describes the general conclusions drawn from this research study.

Concerning targeting of the efficiency improvement of the building elements, the major and deep energy renovation measures in dwellings in temperate climates (to decrease energy use for heating) increase the average and maximum indoor temperatures in room and building level and the overheating risk and overheating period for the occupants. In terms of overheating, the alarming energy renovation measures among the examined cases are the thermal insulation of the floor and the increase of the airtightness of the dwelling. Neutral (slightly positive) contribution offers the increase of the efficiency of the ceiling and wall elements (external insulation) of the building envelope. Positive contribution offers the decrease of the g-value of the windows, inside the existing glazing regulation limits. Rooms on specific orientations and with high window-to-wall ratios have more overheating incidents than the total dwelling on average. For energy renovation projects, thermal comfort analysis in room level for critical rooms is recommended for integration to the guidelines, future national regulations, and comfort Standards. The most effective renovation measure, among the examined ones, in terms of overheating risk, is the installation of the mechanical ventilation system and the application of high air change rates, close to or higher than the capabilities of the systems for domestic use. The higher the efficiency of the dwelling, the higher the performance of the strategy. As part of the renovation measures, mainly external shading systems applied with simple control strategies may diminish the overheating effectively, especially to the Northern temperate climatic conditions.

The numerical analysis of this research study shows that the ventilative cooling method and control strategies through opening systems may be a very energy-effective and sustainable solution for diminishing overheating risk for energy renovated single-family houses, in temperate climatic conditions, without increasing the domestic energy costs only if systems are automated controlled. Indoor air quality based, manual control of the opening systems cannot assure environmental conditions without major overheating incidents and poor air quality. In colder temperate climatic conditions (Nordic countries), automated window opening control systems based on natural ventilation cooling set points and monitoring of the outdoor conditions with integrated simple heuristic ventilative cooling algorithms may significantly diminish the overheating risk. Additional demand control ventilation systems are necessary in some cases for the fulfillment of the minimum air quality requirements. In the hotter temperate climatic conditions (Central Europe), these systems may not be sufficient to eliminate the risk alone. The effectiveness of the examined automated control strategy increases with the increase of application time, also during the day-time. The most critical ventilation parameters for decreasing of overheating incidents are the window opening percentage and the presence of the wind. The indoor natural ventilation cooling set point (trigger ventilative cooling) and the discharge coefficient of the window openings are of low and medium importance respectively.

This research study presents, in detail, a new developed automated window opening control system and highlights its ability to improve the indoor environment, in terms of overheating and air quality of a deep energy renovated representative single-family dwelling in Denmark during the peak cooling season. The developed system improves and optimizes the ventilative cooling capacity of the existing ventilation components. In addition, it provides a more intelligent solution for the control of energy transport through the façade. Integrated control strategies are designed to fulfill the user needs. The indoor thermal and air quality evaluation of the examined dwelling shows that active and passive ventilation components and shading systems, if manually controlled, cannot assure indoor environmental conditions inside the national regulation and comfort Standards limits without major violations. In contrast, the use of the developed window system may significantly diminish the indoor thermal discomfort, assessed by static and dynamic metrics, in all rooms without any significant compromise of the air quality. For this case study, the window system only controls a small part of the available air flow components of the house (roof windows). The thermal comfort assessment of the examined dwelling verifies the findings of the numerical analysis. The low energy use of the developed window systems as well as the total energy savings, more than 95%, from the deactivation of the mechanical ventilation system add extra to the performance value of the system itself. The representation and simulation of the developed window system, on coupled BPS environments, is possible under the proposed workflow and framework. Under this framework, the simulation of any other developed window system or more sophisticated ventilative cooling control strategy is possible.

The comparison and statistical analysis on the overheating metrics of this research study indicates that it is not possible to develop a general relationship between both dynamic metrics and all the examined static metrics. Dynamic indices originate from the same adaptive theory highly correlated with each other, with high adjusted coefficient of determination. Use and inclusion of both indices to the comfort Standards is not suggested. In addition, analysis indicates that it is possible to develop linear relationships between static indices for general use, independently of the building and climate. Double overheating thresholds suggested by a number of national regulations and initiatives is a hyperbole. The DT index statistically cannot be correlated with any other index. Static metrics imposed by national regulations cannot identify all the possible thermal discomfort risks which arise during cooling periods. These issues are mainly related with overheating on lower indoor temperatures and undercooling risk.

CHAPTER 7. FUTURE WORK

Despite the promising findings from the present research study, further investigation on a number of issues is required to fully understand the potentials and limitations of ventilative cooling method and control strategies within building design of energy renovated single-family houses, in temperate climatic conditions.

This research study has examined the combination of a number of different widely applied, well-known, and defined energy renovation measures of building elements, in terms of overheating risk, severity, and duration. Recently, the building industry has presented and promoted a number of new materials and construction techniques for energy renovations, with high market potential in the future. The impact of these new products and techniques to the energy balance of the dwellings during the cooling period is recommended for further investigation. Special interest should be given to products oriented specifically to the heating or cooling seasons. In addition, the effect of the energy renovation measures to other types of residential buildings (like apartments and multi-family buildings) is also suggested to be further examined.

The developed automated window opening control system, with the integrated heuristic passive cooling control strategies and algorithms, has been developed for specific climatic conditions and building type. The application of the system to dwellings with different layouts and structures and for different climatic conditions must be one of the future targets of the development team. The comparison of the developed control algorithms with others, suggested by model predictive control optimization analysis (neural networks) or RBC algorithms from different constructor in the developed coupled BPS environment would highlight the optimum solution and the "energy and comfort penalty gab" for every examined case. For the examined case study, the window system only controls a small part of the available air flow components of the house. A full control of the window and ventilation openings of the house and possible integration with other automated systems (e.g. occupancy detectors and others) would detect non-identified performance advantages or barriers of the system. Occupancy behavior on automate window control systems should also be examined in detail in the future (e.g. log books for specific decisions, as far as the temperature set points and the override actions). The energy penalty from the use of window systems during heating season and transition months, for indoor air quality reasons, in comparison with the mechanical ventilation systems use should also be calculated.

Overheating incidents inside transition months and heating season cannot be cumulated equally in metrics with incidents inside peak summer months. In addition, undercooling incidents during night time in bedrooms seems to be a minor issue. More research with different temperature thresholds, occupancy profiles, climates, and building types-geometries should be conducted in the future for the verification of the recommended statistical relationships. Verification of the models with real data sets from single-family houses in temperate climatic conditions is also suggested. Similar statistical analysis may be conducted also for discomfort metrics including also undercooling incidents.

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PUBLICATIONS FOR THE THESIS

Thesis Title: Ventilative cooling in energy renovated single-family houses in temperate climates

Name of Ph.D. Student: Theofanis Psomas

Name of Supervisor: Professor Per K. Heiselberg

List of Publications:

1) Psomas T, Heiselberg P, Duer K, Bjørn E. Overheating risk barriers to energy renovations of single family houses: Multicriteria analysis and assessment. Energy and Buildings 2016;117:138-48.
2) Psomas T, Heiselberg P, Duer K, Andersen MM. Comparison and statistical analysis of long-term overheating indices applied on energy renovated dwellings in temperate climates. Indoor and Built Environment 2016;0:1-13; DOI: 10.1177/1420326X16683435.
3) Psomas T, Heiselberg P, Lyme T, Duer K. Automated roof window control system to address overheating on renovated houses: Summertime assessment and intercomparison. Energy and Buildings 2017;138:35-46.
4) Psomas T, Fiorentini M, Kokogiannakis G, Heiselberg P. Ventilative cooling through automated window control systems to address thermal discomfort risk during the summer period: Framework, simulation and parametric analysis. Energy and Buildings 2017 (submitted).
5) Psomas T, Heiselberg P, Duer K, Bjørn E. Control strategies for ventilative cooling of overheated houses. Federation of European Heating, Ventilation and Air-conditioning Associations: Proceedings of 12th REHVA World Congress, Aalborg, Denmark. Aalborg University; 2016.

Other Publications:

1) Belleri A, Psomas T, Heiselberg P. Evaluation tool of climate potential for ventilative cooling. Air Infiltration and Ventilation Center: Proceedings of 36th AIVC Conference, Madrid, Spain; 2015.
2) Hidalgo JM, Psomas T, Gáfaro CG, Heiselberg P, Millan JA. Overheating assessment of a Passive House case study in Spain. Air Infiltration and Ventilation Center: Proceedings of 36th AIVC Conference, Madrid, Spain; 2015.
3) Belleri A, Avantaggiato M, Psomas T, Heiselberg P. Evaluation tool of climate potential for ventilative cooling. International Journal of Ventilation 2017 (submitted).
4) Holzer P, Psomas T, O'Sullivan P. International ventilation cooling application database. Federation of European Heating, Ventilation and Air-

conditioning Associations: Proceedings of 12th REHVA World Congress, Aalborg, Denmark. Aalborg University; 2016.

This thesis has been submitted for assessment in partial fulfilment of the PhD degree. The thesis is based on the submitted or published scientific papers which are listed above. Parts of the papers are used directly or indirectly in the extended summary of the thesis. As part of the assessment, co-author statements have been made available to the assessment committee and are also available at the Faculty.

Appendix I

Article 1

Psomas T, Heiselberg P, Duer K, Bjørn E. Overheating risk barriers to energy renovations of single family houses: Multicriteria analysis and assessment. Energy and Buildings Journal 2016;117:138-48.

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Overheating risk barriers to energy renovations of single family houses: Multicriteria analysis and assessment

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ABSTRACT

Many post-occupancy comfort studies of energy renovated residential buildings have documented elevated temperatures above comfort levels, not only during the summer period but also during the shoulder months. The main focus in renovation projects is on heat savings while the risk of overheating is not considered.

This paper analyze in which situations overheating and cooling need to be addressed in building energy renovation projects and which renovation measures are causing this need. The analysis contains four reference single family houses from central and northern Europe. Both dynamic and static methods were used to assess the overheating risk.

In terms of overheating occurrences, the most critical renovation measures are the insulation of the floor and the increase of the airtightness. The contribution of decreasing the g value of the window glazing is positive. The way to energy efficiency improvements also results in an extension of the overheating period and higher average and maximum building temperatures. The increase of the ventilation rates and the use of shading systems are useful measures for preventing overheating increase. The paper will highlight the inconsistencies which arise from the use of different criteria and also propose suggestions for future work.

1. Introduction

The building sector is responsible for more than one third of the energy use [1] and carbon emissions in the European Union [2]. The greatest share of the building stock is residential (75%) and the majority of them (64%) are single-family houses [3]. Energy efficiency improvements of the existing stock are one of the most cost-effective ways to reduce energy use, achieve emission targets, fight climate change and fuel poverty, improve competiveness, as well as create employment in Europe [3–5].

Directive 2012/27/EU urges member states to establish a long-term strategy for investments in building renovation. The current goal of the council is to have the total amount of the existing stock be renovated by 2050. The renovation rate has decreased to less than 1% [2] mainly because of the economic recession. Most renovation activities at the moment achieve only modest energy savings [3]. Energy renovations are made as an integrated part of other refurbishment processes (internally or externally). Deeper and nearly zero energy (nZEB) renovations, as analyzed in [4], are expected in the European countries in the coming decades if the full economic and social potential are to be realized.

Various researchers have studied the implication of energy measures to nearly zero energy renovations mainly concerning the colder conditions in winter [6–8]. However, in many post-occupancy comfort studies elevated temperatures have been documented [9,10] not only during the summer period but also during the shoulder months, even in Central and North Europe [11,12]. Overheating risk assessment in houses was not the main research topic until recently [13]. For the building designers, builders and

Abbreviations: ACH/hr, air changes per hour; AUS, Austrian case study; DK, Danish case study; E, external shading system; EPS, expanded polystyrene; EU, European Union; F, fixed shading system; FR, French case study; G, Solar heat gain coefficient; I, internal shading system; ISO, International Organization for Standardization; n_{50}, Air change rate at 50 Pa (pressure test); nZEB, nearly zero energy building; NE, North east orientation; SW, South west orientation; $_{\mathrm{i.oper,max}}$, max value of indoor operative temperature due to the comfort model (°C); T_{rmr}, running mean outdoor temperature (°C); U, heat transfer coefficient; U.K., British case study; XPS, extruded polystyrene.

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occupants cooling and overheating risks are unknown challenges that they have not experienced before and as there is no previous experience the need for cooling is underestimated [11,12]. In addition, thermal demand calculations of renovated buildings are based on simplified monthly methods, averaging the need for cooling both in time and space [14].

Evidences show that high indoor temperatures for long periods cause serious impacts to the indoor environmental quality and result in a very important seasonal increase of morbidity [15] and mortality [16,17]. Climate change resulting in warmer years and increases in heat waves especially in cities of central and northern Europe (heat island effect) will affect the thermal quality indoors [18].

The scientific literature holds no rigorous or accepted definition of what constitutes overheating in buildings [15]. Most of the definitions are health, productivity or thermal comfort related [15]. The ISO 7730, [19] and EN 15251 standards [20] define the range of indoor thermal environmental conditions acceptable to the majority of occupants. During the last decade, a new type of indices has been proposed, describing in one number the long-term thermal discomfort conditions in spaces, like overheating [21]. Most of the indices referred to the occupied period [22]. These indices are widely used for operational assessment of comfort in existing buildings and optimization of the envelope and the control strategies in the design phase [22].

The main objective of this paper is the investigation and assessment of the overheating risk (time and intensity) with the use of well-known and documented methods and indices for representative residential single-family houses in room level under different stages of renovation. The research results will indicate under which conditions (combination of renovation measures and depth of renovation) overheating and cooling need to be addressed in building energy renovation projects. The analysis will be conducted for various temperate and Mediterranean climates. The secondary objective of the paper is the investigation of the inconsistencies, which arise from the use of different methods at the assessment comfort analysis. This research will contribute to the ongoing discussion about the effectiveness and the necessity of these indices with possible amendments to the new comfort standards. Suggestions for improvements and future work are also proposed.

2. Methodology

2.1. Case studies

The European Union council has established the concept of national or regional reference buildings for investigation of the cost optimal measures of minimum energy performance requirements [23]. During the last decade, extended research has been conducted trying to define and propose typical representative buildings and framework for archetypes around Europe [24,25]. Building typologies may be a useful tool for policymakers and designers to understand energy performance of the stock and to suggest possible energy savings at regional or country level [25]. The main characteristics of the existing literature are a lack of common definitions and the absent of updated statistical data in many cases [26–28]. The "*Typology Approach for Building Stock Energy Assessment*"[1] project has a reference position regarding the definition of typical residences (single-family, terraced, apartments and multifamily) for 13 European countries [25].

This research involves investigation of four different reference buildings and climates [29], U.K. (London city); Denmark

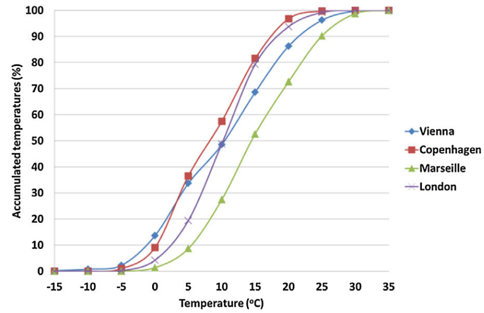


Fig. 1. Accumulated outdoor temperatures (%) of the examined locations (Vienna, Copenhagen, Marseille, London).

(Copenhagen); Austria (Vienna) and South France (Marseille, H3 climatic zone of France), Fig. 1. These weather conditions (Fig. 1) are representative of the climates of central and northern Europe [29]. The stock of these countries equates with one third of the European Union building stock [3]. In addition, two out of four countries (U.K. and France) have faced tremendous losses with thousands of deaths from heat waves and unusual high indoor temperatures in the previous decade [15].

The case studies of the paper are reference buildings by definition, as far as the geometry, energy performance, materials, window area and structure of these countries for the specific periods (1970's and 80's) are concerned. Two out of the four case studies are real buildings from Table project (Denmark, France, Fig. 2). The other two cases are analyzed at the official reports of the examined countries to the European commission [30,31] and are the result of deep statistical analyses through the energy certificates.

The houses of these periods were constructed before or with the first energy regulations and they will be deeply renovated in the coming years (high market potential). Table 1 presents the thermal and technical characteristics of the used cases. In most of the case studies, apart from the external geometric characteristics of the buildings, the information provided only goes as far as the thermal conductivity of the materials (elements), the thermal characteristics of the windows, the infiltration values, the thermal bridging, the general living patterns and the mechanical equipment of them. The missing thermal characteristics of the materials were extracted from International Standards [32] and the technical details of the buildings from various sources and authors [6,7,33–35].

The case studies represent typical heavy-weight constructions from bricks and concrete block elements. The insulation materials were placed inside the walls (foam) and over the wooden ceiling under the unoccupied attic (mineral wool). The floor elements are based on the ground (soil) typically constructed by heavy-weight armed concrete, light-weight concrete and tiles (high thermal mass). The windows in most of the case studies are with single glazing and wooden frames. The internal heights of the buildings are from 2.3 m (Denmark) to 2.5 m (U.K.).

For the investigation of the overheating risk at room level internal floor plans were developed. The common characteristic of the plans are the two similar bedrooms (6.3 m^2 of net floor area) facing the north and east orientations (NE bedroom) and the south and west orientations (SW bedroom).

2.2. Renovation packages

The applied renovation packages of the reference houses are divided into two categories: (1) the measures which refer to the efficiency of the elements (Group A) and (2) the measures which

[1] http://webtool.building-typology.eu/webtool/tabula.html (December, 2014).

Table 1
Thermal and technical characteristics of reference case studies for different countries and different renovation phases.

a/a	Period	U_{wall} (W/m²K)	$U_{ceiling}$ (W/m²K)	U_{floor} (W/m²K)	U_{window}, g (W/m²K), -	Infiltration n_{50} (ACH/hr)	Storey	Net floor area (m²)
Austria (After 1960), [30]								
Base Case-P1		1.2	0.55	1.35	3.0, 0.67	3	2	144.4
Deep Renovation-P2		0.27	0.15	0.3	1.2, 0.6	1.5		
nZEB Renovation-P3		0.15	0.15	0.15	0.8, 0.5	0.6		
Denmark (1973–1978), [14]								
Base Case-P1		0.45	0.45	0.35	2.7, 0.76	5	1	116.2
Deep Renovation-P2		0.2	0.15	0.12	1.65, 0.7[a]	1.6		
nZEB Renovation-P3		0.2	0.15	0.12	1.2, 0.6[b]	0.8		
France (1982–1989)[c]								
Base Case-P1		1	0.6	1	4.6, 0.9	5	1	94.2
Deep Renovation-P2		0.43	0.22	0.43	1.5, 0.7	1.4		
nZEB Renovation-P3		0.15	0.15	0.15	0.8, 0.5	0.6		
U.K. (Before 1978), [31]								
Base Case-P1		2.25	0.85	1.35	3.2, 0.8	8	2 (semi detached. North)	60.3
Deep Renovation-P2		0.3	0.18	0.2	1.6, 0.7	4		
nZEB Renovation-P3		0.15	0.15	0.15	0.8, 0.5	0.6		

P1: Phase 1, P2: Phase 2, P3: Phase 3 (explained below).
[a] 2015 Danish regulations [Appendix F, 14].
[b] 2020 Danish regulations [Appendix F, 14].
[c] Niveau RT existant (article 7), 29.9.2009.

refer to the systems (mechanical ventilation, shading systems) of the building (Group B). The renovation measures are also analyzed in three phases. The first phase will contain analysis of the initial base case study as extracted from the reports (symbol o in Table 2). The renovation targets of many countries coincide with the cost-effective measures for renovation due to the European Directive [14,23,30,31]. In the second phase (symbol + in Table 2) the case studies are renovated, according to the regulations of each country (2013, [30,31]) in steps (Tables 1 and 2). The procedure is explained below:

- Replacement of windows.
- Improvement of the physical characteristics of the ceiling.
- Improvement of the physical characteristics of the external walls.
- Improvement of the physical characteristics of the floor.
- Improvement of the airtightness.

Typically, owners in real cases renovate dwellings for financially reasons in steps. The typical work flow and sequence of actions is the replace of the windows (less invasive renovation) then the insulation of the ceiling and the external walls and at the end the insulation of the floor elements (most invasive renovation). These renovations in many cases take months or years. The same approach is followed also in this research (Table 2). Every renovation variant has one or two additional renovation improvements compared to the previous one. With this work flow for every country they created 7–9 different renovation variants (Table 2). The improvement of the airtightness of a building is a process related with all the stages of the renovation. The airtightness improvements are represented as a different variant because the authors would like to separately highlight the effect of this to the overheating risk of a building. The use of the external insulation systems instead of the internal systems is related with the decision for exploitation of the high thermal mass of the building (graphite EPS for the walls, mineral wool for the ceiling and high compressive strength XPS boards for the floor elements). The validity of the regulations of each country is outside the scope of this paper. The regulation targets were used only as intermediate steps into the energy efficiency.

In the third phase (symbol ++ in Table 2) of the simulations, the case studies (Tables 1 and 2), were renovated to reach very efficient energy goals (nZEB, [4]). The thermal characteristics of the envelope elements are based either on guidelines of Passive House standards[2] or on the 2015 Danish building regulations [14].

In many cases the energy renovation of the house is accompanied with the installation of new mechanical ventilation systems with heat recovery for the diminishing of the winter ventilation losses (also higher capacity). In addition, in many cases, new efficient windows are accompanied with shading systems as a package. For the fulfillment of the analysis, two additional renovation packages, which prevent the increase of the overheating risk indoors, were analyzed (Table 3).

The systems above were applied in two out of four case studies (Denmark and South France), at the end of every phase (full compliance).

Three different shading systems have been analyzed:

- internal venetian blinds with high reflectivity (0.8)
- external slat blinds with high reflectivity (0.8) and
- fixed pergolas-awnings (0.5 m projected)

[2] http://www.passivehouse-international.org/index.php?page_id=80 (December, 2014).

Fig. 2. Examined case studies for Denmark (left) and South France (right), TABULA project.

Table 2
Renovation packages (Group A) for reference case studies for different phases and locations.

Renovation Variant	Phase	Windows	Ceiling	External Wall	Floor	Airtightness
AUS_0	1	o	o	o	o	o
AUS_1	2	+	o	o	o	o
AUS_2		+	+	o	o	o
AUS_3		+	+	+	o	o
AUS_4		+	+	+	+	o
AUS_5		+	+	+	+	+
AUS_6	3	++	+	+	+	+
AUS_7		++	++	++	++	+
AUS_8		++	++	++	++	++
DK_0	1	o	o	o	o	o
DK_1	2	+	o	o	o	o
DK_2		+	+	o	o	o
DK_3		+	+	+	o	o
DK_4		+	+	+	+	o
DK_5		+	+	+	+	+
DK_6	3	++	+	+	+	+
DK_7		++	+	+	+	++
FR_0	1	o	o	o	o	o
FR_1	2	+	o	o	o	o
FR_2		+	+	o	o	o
FR_3		+	+	+	o	o
FR_4		+	+	+	+	o
FR_5		+	+	+	+	+
FR_6	3	++	+	+	+	+
FR_7		++	++	++	+	+
FR_8		++	++	++	++	+
FR_9		++	++	++	++	++
U.K._0	1	o	o	o	o	o
U.K._1	2	+	o	o	o	o
U.K._2		+	+	o	o	o
U.K._3		+	+	+	o	o
U.K._4		+	+	+	+	o
U.K._5		+	+	+	+	+
U.K._6	3	++	++	+	+	+
U.K._7		++	++	++	++	+
U.K._8		++	++	++	++	++

o stands for the initial base.
+ stands for the deep renovation.
++ stands for the nZEB renovation.

The movable shadings systems are applied to all the affected orientations and windows during the unoccupied hours (Table 4).

The second examined measure simulated as an increase of the ventilation airflow rate from the basic value (0.5 ACH/hr for indoor air quality reasons) to 1.5 ACH/hr in two steps. Reduced ventilation flow below the value of 0.5 ACH/hr may cause a perception of impaired air quality in dwellings [36]. The new rates are applied all day for every room. The constant use of the mechanical ventilation system is typical for a lot of new houses without control buildings systems, because the owners either do not want to be involved in the control of the house or do not understand how the systems work [36].

2.3. Long-term overheating indices

This paper uses two well documented and widely applied indices for the assessment of the overheating indoors. The first index is referred to the EN15251 European adaptive method [20]. The index measures the percentage of the occupied hours (Table 4) with operative temperatures higher than the upper bound of the adaptive comfort temperature (Eq. (1), Fig. 3). In our cases for renovated residences, Category II is been used [20]. This category refers to normal level of comfort expectations and suggested from the standards for new buildings and renovations [20]. High level of expectation (Category I) is recommended for spaces occupied by

Table 3
Renovation packages (Group B) for reference case studies for different phases and locations.

Renovation Variant	Ventilation rate (1 ACH/hr)	Ventilation rate (1.5 ACH/hr)	Shading system (internal)	Shading system (external)	Shading system (fixed)
DK_0_1	√				
DK_0_1.5		√			
DK_0_I			√		
DK_0_E				√	
DK_0_F					√
DK_5_1	√				
DK_5_1.5		√			
DK_5_I			√		
DK_5_E				√	
DK_5_F					√
DK_7_1	√				
DK_7_1.5		√			
DK_7_I			√		
DK_7_E				√	
DK_7_F					√
FR_0_1	√				
FR_0_1.5		√			
FR_0_I			√		
FR_0_E				√	
FR_0_F					√
FR_5_1	√				
FR_5_1.5		√			
FR_5_I			√		
FR_5_E				√	
FR_5_F					√
FR_9_1	√				
FR_9_1.5		√			
FR_9_I			√		
FR_9_E				√	
FR_9_F					√

I: stands for internal shading system.
E: stands for external shading system.
F: stands for fixed shading system.

Table 4
Occupancy (2 person (pr) and 5 person (pr)) and internal gains profile (5 pr) of the reference case studies.

Time/day	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Internal[a] gains (W/m^2)
1	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	2.1
2	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	1.5
3	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	1.3
4	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	1.3
5	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	1.3
6	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	1.3
7	5pr, 1pr	5pr, 1pr	5pr, 1pr	5pr, 1pr	5pr, 1pr	5pr, 2pr	5pr, 2pr	1.5
8	5pr, 1pr	5pr, 1pr	5pr, 1pr	5pr, 1pr	5pr, 1pr	5pr, 2pr	5pr, 2pr	1.7
9	–	–	–	–	–	5pr, 1pr	5pr, 1pr	2.1
10	–	–	–	–	–	5pr, 1pr	5pr, 1pr	2.3
11	–	–	–	–	–	5pr, 1pr	5pr, 1pr	2.7
12	–	–	–	–	–	3pr, 1pr	3pr, 1pr	2.5
13	–	–	–	–	–	3pr, 1pr	3pr, 1pr	2.5
14	–	–	–	–	–	3pr, 1pr	3pr, 1pr	2.5
15	–	–	–	–	3pr, 1pr	3pr, 1pr	3pr, 1pr	2.7
16	–	–	–	–	3pr, 1pr	3pr, 1pr	3pr, 1pr	2.7
17	3pr, 1pr	3pr, 1pr	3pr, 1pr	3pr, 1pr	3pr, 2pr	3pr, 2pr	3pr, 2pr	2.9
18	3pr, 2pr	3pr, 2pr	3pr, 2pr	3pr, 2pr	3pr, 2pr	3pr, 2pr	3pr, 2pr	3.2
19	3pr, 2pr	3pr, 2pr	3pr, 2pr	3pr, 2pr	3pr, 2pr	3pr, 2pr	3pr, 2pr	3.4
20	3pr, 2pr	3pr, 2pr	3pr, 2pr	3pr, 2pr	3pr, 2pr	3pr, 2pr	3pr, 2pr	3.6
21	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	3.6
22	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	3.8
23	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	3.0
24	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	5pr, 2pr	2.7

[a] 5 members family internal gain profile (equipment and lightning).

very sensitive and fragile persons with special requirements. The method is symmetric, comfort based and category dependent [22]. The hours with undercooling (temperatures lower than the adaptive comfort model boundaries) are outside the scope of the paper.

$$T_{i,op.max} = 0.33 \times T_{rm} + 21.8 \tag{1}$$

$T_{i,op.max}$: limit value of indoor operative temperature (Category II, °C)

T_{rm}: running mean outdoor temperature (°C).

The second index measures the percentage of occupied hours (Table 4) with operative temperatures above fixed thresholds, 26 °C for bedrooms (building) and 28 °C for living room (static method, [37]). These benchmarks are not depended on any comfort model, are assymetric and do not refer to any categories [21]. The guidelines [37] suggest special summer weather data and specific investigation period (1 May–30 September). For generalization of

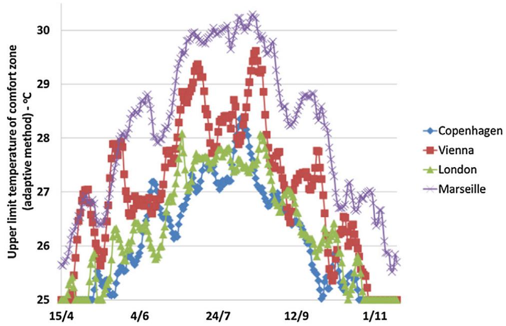


Fig. 3. Upper limit of the adaptive thermal comfort model range for all the cases from 15th April to 15th November (Category II-EN 15251:2007).

our research well documented updated Energy Plus weather data from the examined areas were used (Fig. 1). Furthermore, the renovation in many cases results in the extension of the overheating period. For this reason this research examines the overheating risk for the whole year. This static method is the most widely used method for long-term assessment of overheating risk in the literature and the legislations of the countries. The thresholds and the hours of exceedance vary from country to country [14,22]. For multi-zone model assessment the operative temperature of the building is calculated by weighing the temperatures of all the zones of the house in net volume terms [20].

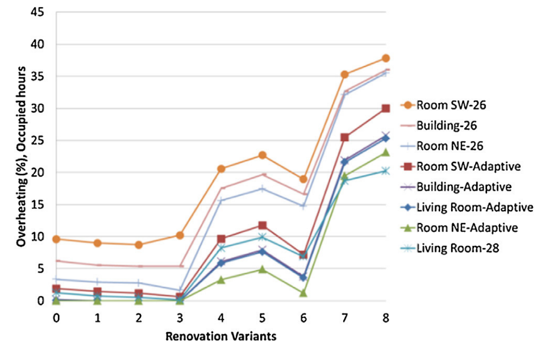
2.4. Dynamic energy simulations

Building thermal simulation algorithms are tools that are able to represent the physics of overheating occurrence close to reality [38,39]. Analyses were conducted with the use of highly sophisticated and state of the art building performance simulation tool DesignBuilder version 4.2. This software uses the calculation engine of Energy Plus v. 8.1 and complies with the state of the art European and ASHRAE energy guidelines and standards [40,41].

For the simulation of the heat conduction of the envelope the Conduction Transfer Function algorithm was used [40]. The natural convection heat exchange was simulated internally with the use of the TARP method and externally with the DOE-2 method [40]. The time steps of the simulation were set to 4 per hour for accuracy reasons (26 days of warmup). The weather files used in the simulations were Energy Plus files (.epw format) with hourly data [41]. The examined weather data[3] referred to the previous decade and they are representative of the climatic conditions of these cities (Fig. 1), [41]. The heating set point was set to 20 °C. The case studies were simulated as free floating buildings (transition and summer season), without mechanical cooling systems. The simulations were conducted with constant 0.5 ACH/hr all day for indoor air quality reasons [36]. Constant ventilation rate of 0.5 ACH/hr is currently a minimum standard in many European countries and regulations for indoor air quality reasons [36]. This value is the minimum requirement in the Danish building code for more than 20 years [36,14].

Two occupancy profiles were used for these analyses. The first main profile reflects a 5-member working family and the second a 2-member working couple [42,43]. Table 4 shows the daily profiles analytically (all week). The internal load (equipment and lighting) profile for the 5-member family is presented also in Table 4 [44]. The internal gains from the occupancy were simulated additionally. The used internal gain profile (weighted average for the total European area and all year) is the result of an extended European project [44]. Twelve countries were involved and more than 11,500 appliances were analyzed. Two out of four examined countries (Denmark and France) have participated also on this project. The internal gains refer to the net floor area of the cases (m^2). The decrease of the internal loads for the second profile (2 pr) is based on Jensen's conclusions (54.8% decrease), [42]. The second profile is applied only for the two climatically extreme cases and only for the renovation packages of Group A. This analysis highlights the sensitivity of the overheating occurrence to these design parameters (occupancy and internal loads).

[3] http://apps1.eere.energy.gov/buildings/energyplus/weatherdata_about.cfm (December, 2014).



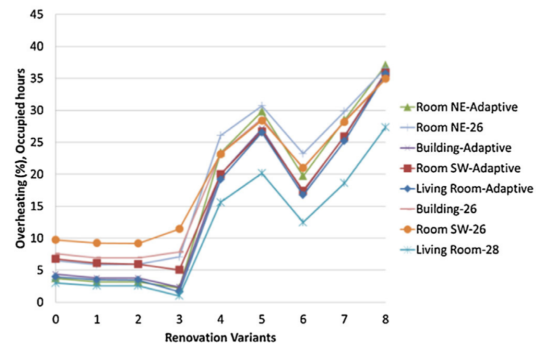


Fig. 4. Percentage of overheating hours (occupied) for different renovation variants (Table 2) in room level for both methods, for the Austrian case study (up) and for the British case study (down).

3. Results and discussion

3.1. Group A renovation packages

3.1.1. Austria–U.K.

Fig. 4 presents the percentages of occupied hours with overheating for both methods, different renovation measures, rooms and case studies (Tables 1 and 2). The way to building energy efficiency, without extra passive or active cooling measures, leads to the increase of the overheating occurrence indoors. In general, both methods show similar patterns and critical renovation measures. The static method always shows higher overheating values compared with the adaptive one for every retrofit variant and room. For the British house, this deviation of the methods is minimal. Especially for renovation variant 8, the differences of the outputs are almost negligible. The static method was promoted by the British Building Institute [36] before the spreading of the adaptive concept around Europe. The British case study presents the highest

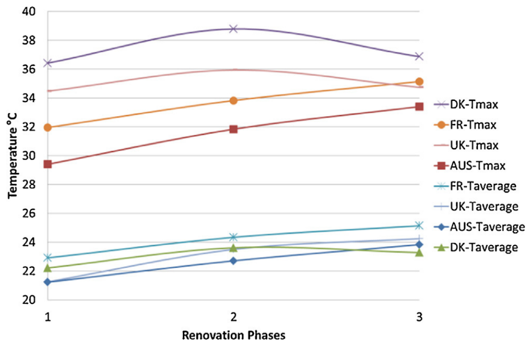


Fig. 5. Yearly average and maximum building operative temperatures for all case studies for different renovation phases (end).

values among all the case studies for both phases 2 and 3 (adaptive method). In addition, rooms facing the southwest orientation overheated more compared with others for both methods and phases. In this room, the yearly average and maximum operative temperatures are also higher.

The renovation variants with measures for windows, ceiling and external walls (variants 1–3, Table 2) of phase two, slightly decrease the discomfort conditions of the building in both cases. The decrease of the thermal characteristic of the windows in these variants is high as far as the heat transfer coefficient is concerned but negligible in the *g* value coefficient (Table 1). The *g* value coefficient of solar gains seems to be the critical parameter, as far as the diminishing of these overheating risk indices (variants 6) is concerned.

On the other hand, additional floor insulation and improvements of the airtightness (variants 4, 5, 7 and 8) increase overheating hours in renovation phases two and three for both methods of assessment. Floor insulation seems to be the most critical renovation measure in terms of overheating hours for both methods and case studies. These results verify the important role of floor and earth as heat sinks during the hotter months of the year.

Renovation also increases average and maximum indoor temperatures (Fig. 5). For the Austrian house the period with overheating incidents extended from June to August (base case); to May to October (variant 8, adaptive method). The month with the most overheated hours is July (variant 5) and August (variant 8). For the British house overheating starts from May and finishes in September (variant 8, adaptive method). The month with the most overheated hours is July (variant 5) and August (variant 8).

3.1.2. Denmark–France

Fig. 6 presents the percentages of occupied hours with overheating for both methods, different renovation packages, rooms and case studies (Tables 1 and 2). Similar conclusion regard the risk of overheating indoors because of the increase of the efficiency of the building elements and the critical renovation measures and rooms may be extruded (Section 3.1.1). Danish regulation for cost-optimal retrofit goals was set at the end of 2010 in parallel with the adoption of 2015 and 2020 goals (new buildings) [14]. The 2020 energy goals of phase 3 for the particular Danish house may be succeeded with measures related with the improvements of the airtightness and the glazing. These renovation measures are antagonistic in terms of overheating risk. As a result the outputs of the analyses are almost coinciding (variants 5 and 7). For these cases the deviation of the methods is important for every phase and package. The French house presents the highest values for both phases with the static method. Fig. 5 shows the yearly average and

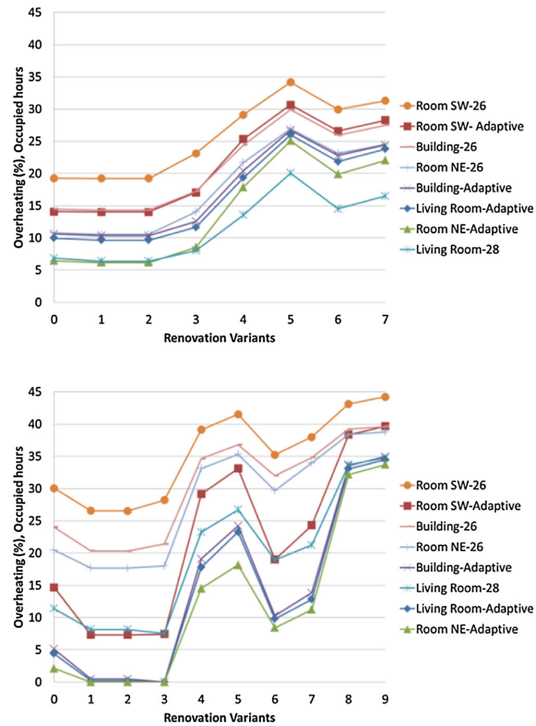


Fig. 6. Percentage of overheating hours (occupied) for different renovation variants (Table 2) in room level for both methods, for the Danish case study (up) and for the southern French case study (down).

maximum building operative temperatures for the end of every phase. The Danish house presents the highest maximum temperature of all the cases. The high internal temperatures are related with high spring and summer solar gains from low sun angles. For the Danish house the uncomfortable temperatures starts from May and lasts until October, (variants 5 and 7, adaptive method). The month with the most overheated hours is July (variants 5 and 7). The French case study shows the highest average building temperatures for every phase. The period with uncomfortable temperatures extends from May-September (variant 5) to April-September (variant 9, adaptive method). The month with the most overheated hours is July (variant 5) and August (variant 9).

Fig. 7 presents the results for different occupancy levels (2-person couple), assessed by two methods for the two climatically extreme case studies. The decrease in overheating occurrences for different phases of renovation is from 2.9% to 8.6% (in relative terms) for dynamic method and from 3.2% to 6.8% for static method for the Danish house, and from 1.8% to 9.3% (in relative terms) for dynamic method and from 3.1% to 3.6% for static method, for the southern French house. The adaptive method seems to be more sensitive in both cases to different internal loads (occupancy and equipment). Finally, the more efficient the building, the more important the role of the internal loads to the assessment of overheating risk.

3.2. Group B renovation packages

Renovation measures of this group are actually antagonistic measures and decrease the overheating risk indoors (Table 3).

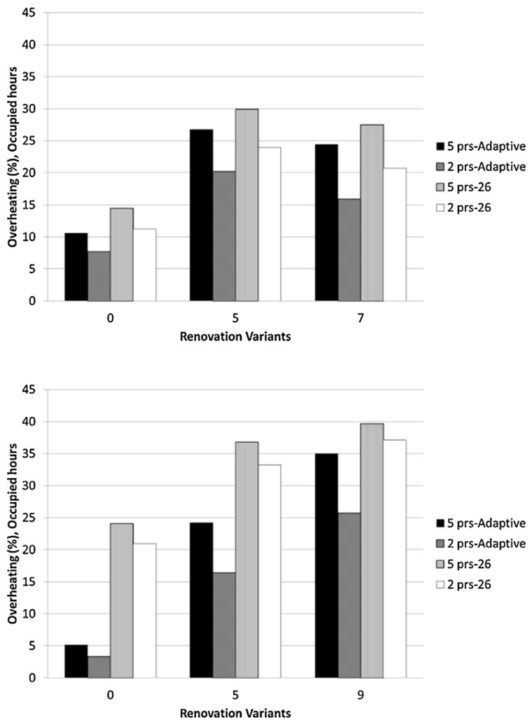


Fig. 7. Percentage of overheating hours (occupied) for different renovation variants (Table 2) and occupancies for both methods, for the Danish case study (up) and for the southern French case study (down).

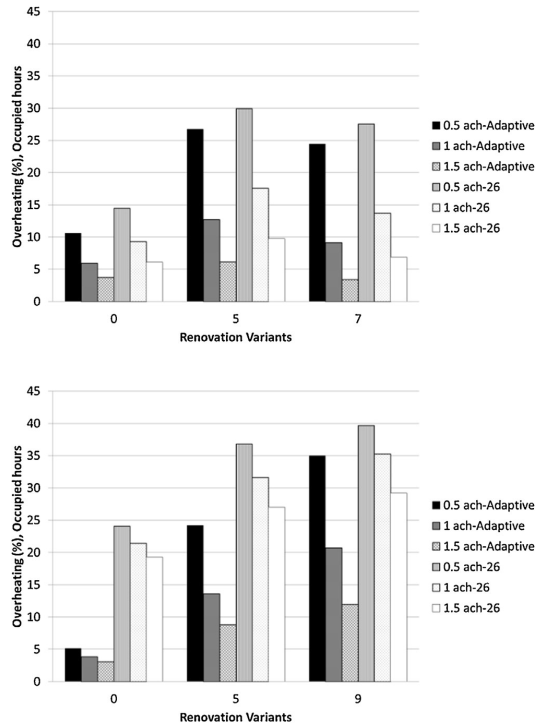


Fig. 8. Percentage of overheating hours (occupied) for different renovation variants (Table 2), methods and ventilation rates, for the Danish case study (up) and for the southern French case study (down).

Fig. 8 presents long-term overheating risk indices for different renovation variants and ventilation air changes for both methods and two cases (Table 3). In general, the increase of the ventilation air change dramatically decreases the overheating occurrence indoors. For both case studies the higher the efficiency of the building, the higher the effectiveness of the measure. In the Danish house both methods show similar outputs. In the French case the two methods show discrepancies.

A lot of designers of high efficient buildings suggest to the owners the increasing of the air changes of the mechanical ventilation systems during the transition and summer periods (no use of windows). The constant operation of the system during the whole day increases slightly the energy consumption of the house but guarantee excellent indoor conditions in terms of air quality and acceptable limits of overheating. Various researchers have analyzed in depth the constraints and limitations of the manual use of the windows of a house [45–47].

As far as the shading analysis (Fig. 9) goes, the use of external movable blinds or fixed systems decreases the indices approximately 50% in the Danish case for both methods. The application of the internal blinds decreases the occurrence by approximately 25%. The two most efficient shading systems seem to have similar results for both cases and methods.

For the French case the shading systems are not very effective, independently of the assessed method. The fixed systems are more effective than the movable (external). In this case the overheating occurrence depends more on the high outdoor temperatures and less on the orientation and magnitude of the solar gains. The internal blind system seems somewhat ineffective for this case study measured by both methods. Similar conclusions also extruded for room level analyses (not illustrated). The shading systems (movable) for these houses are in use only during the unoccupied hours (Table 2). Various researchers have analyzed in depth the constraints and limitations of the manual use of the shading systems of a house [48]. The most effective antagonistic measure is the increase of the ventilation rates (1.5 ACH/hr) for every case study and phase.

Fig. 10 presents the yearly average and maximum building temperatures for both measures (Group B) and in all phases (end) of the case studies. Both cases show the lowest average temperatures with increased ventilation rates (1.5 ACH/hr). For the Danish case the lowest maximum temperature occurred with the use of fixed shading systems. Finally there is an important decrease of the overheating period after the application of the packages (Group B) for every case study. These results are not illustrated.

Fig. 11 presents all the renovation variants of the two houses (Denmark, southern France) ranked in descending order in terms of average operative building temperature (occupied hours). The static methods of the two buildings follow the continuous decreasing trends of the average operative temperatures with small deviations or peaks. The adaptive method shows also a decreasing trend but with more deviations, especially for the French house. Spearman's coefficient provides information of how well a monotonic function represents a relationship between two ranked variables (overheating index and average building temperature), [21]. The values for the Danish house for the two methods are 0.98 and 0.99 respectively and for the French house 0.98 and 1.00 respectively. The explanation for these minimum differences is that the adaptive method considers not only physical

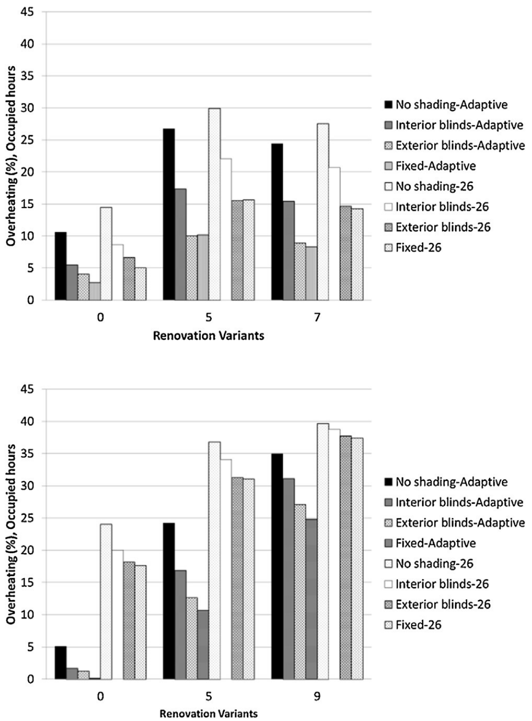


Fig. 9. Percentage of overheating hours (occupied), for different renovation variants (Table 2), methods and shading systems, for the Danish case study (up) and for the southern French case study (down).

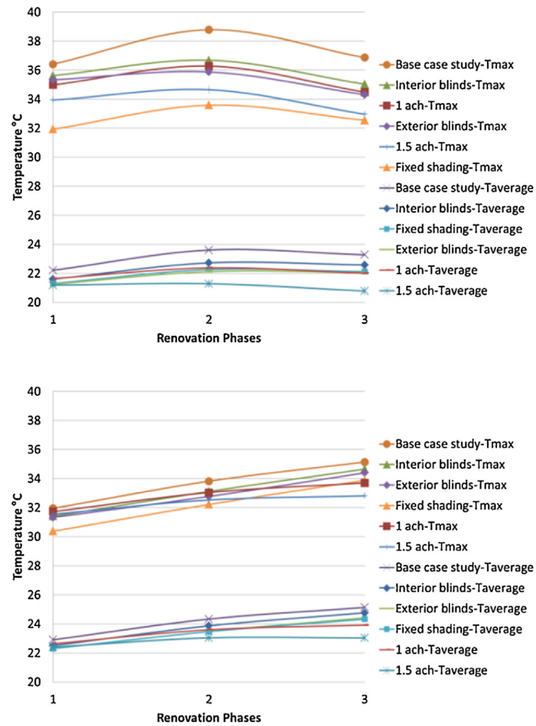


Fig. 10. Yearly average and maximum building operative temperatures for Danish (up) and southern French (down) case study for different renovation phases (end) and different renovation packages (Group B).

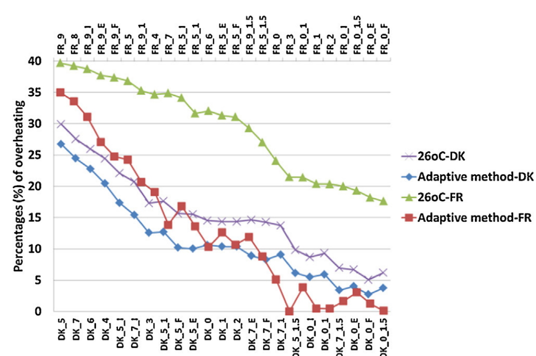


Fig. 11. Ranking of all the renovation measures in terms of average operative building temperature (occupied hours), for the Danish (lower x axis) and southern French (higher x axis) case study.

quantities but also psychological or personal factors and possibilities for interaction with the external environment [32]. The coefficients for both methods and cases are quite high, indicating that these two ranked variants may offer similar information to the designers, as far as the overheating risk is concerned.

4. Conclusions

One of the most important barriers to retrofitting houses is financing. For this reason it is very important that these improvements of the energy efficiency of the building to be accompanied by high quality thermal indoor conditions. This paper presents the results of multi-zone dynamic thermal analyses of four representative houses with high retrofit market potential, from central and northern Europe (Austria, Denmark, France, U.K.) in terms of the indoor thermal quality and the risk of overheating in room level, for different renovation packages. The overheating occurrence was assessed by both dynamic and static methods.

The increase of the energy efficiency of the single-family houses, through renovation without using passive or active cooling systems, results in an alarming increase of the overheating risk indoors. The critical measures are the insulation of the floor and the decrease of the airtightness. Positive contribution to reducing the overheating risk is the decrease of the g value of the windows. Small positive or negative contributions to overheating occurrence cause the increase of the efficiency of the walls and/or ceiling. Increase of the energy efficiency of a house results also an extension of the overheating risk period. The increase of the overheating occurrence is accompanied with changes to the average and maximum temperatures indoors. Particularly rooms at the critical orientations may be overheated more compared to others. This information has to alarm the designers to consider the overheating risk and cooling need in building energy renovation projects and to consider performing thermal comfort and cooling need analyses both on building and well as on individual room level. Design of extra systems to specially exposed rooms should also be considered, even in cases where the building, in average, fulfills the overheating targets of the regulations or standards. The static method for overheating assessment almost always presents higher risk compare to the dynamic method. For the northern locations the two methods give approximately similar results. This difference becomes significant as we transfer to the southern climates. The adaptive method seems to be more sensitive to changes regarding the internal loads of the building. The more efficient the building, the more important the role of the internal loads to the assessment of overheating risk.

The increase of the ventilation rates close to 1.5 ACH/hr, may contribute to the diminishing of the negative comfort results of the energy renovation. The shading systems are well documented passive cooling systems that may diminish the examined comfort problem effectively, especially to the northern countries. The external shading systems (movable or fixed) improve the thermal conditions better than the internal systems, especially at the northern locations. For both cases the higher the efficiency of the building, the higher the effectiveness of these measures.

This analysis shows high correlation of the examined overheating indices with average building temperatures. The ranking capabilities of the three parameters for the renovation packages are almost identical.

Boundaries regarding the periods for overheating examination should be set to the new standards and guidelines. Overheating incidents inside heating periods cannot be cumulative with those in the middle of the cooling periods. The investigation of different overheating risk indices for different climatic conditions and types of buildings is suggested for further work in the future.

Acknowledgements

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Appendix II

Article 2

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Comparison and statistical analysis of long-term overheating indices applied on energy renovated dwellings in temperate climates

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Abstract

Stakeholders, researchers and designers apply different overheating metrics because they follow different comfort theories or comply with different regulations and standards. As a result, there is no common ground for generalization, intercomparison and final concordance of their conclusions. Correlation of indices would simplify the analysis being conducted during the design (optimization process) or operational (comfort assessment) phase of buildings. This research compares and statistically correlates results of seven widely used long-term overheating indices on four 'free-running' representative dwellings and characteristic climatic conditions of central Europe (Denmark, United Kingdom, Austria and France). Different renovation steps and passive cooling strategies were applied on these case studies creating 66 variants for comfort assessment. The analyses were conducted with the use of a dynamic energy performance engine and widely accepted calculation methods and statistical tools. The statistical analyses show that dynamic indices originate from the same adaptive comfort theory directly related with each other. In addition, it is possible to create general and widely applied relationships between static overheating indices independently of the case study and climatic condition.

Keywords

Single-family house, Thermal comfort, Overheating risk assessment, Energy efficiency, Adaptive comfort, Residential building, Indoor environment

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Introduction

The greatest share of the building stock of the European Union is residential buildings (75%) and more specifically single-family houses amount to approximately 48% of the total stock.[1] Increasing energy efficiency of the building stock is one of the most cost-effective ways to decrease energy use and carbon emissions, to decelerate climate change and increase employment demand and competiveness.[2] Post-occupancy comfort studies through questionnaires and monitoring of deep energy renovated or nearly zero energy dwellings have documented elevated temperatures over the limits of regulations and standards, not only during the cooling period but also during the transition months.[3] Overheating is identified as an important health problem in residences.[4] High indoor temperatures outside the thermal comfort range, for long periods, cause serious impact on indoor quality and vulnerability. Overheating in energy renovated dwellings of temperate climates has so far not been considered as a design challenge.

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There are a variety of thermal comfort models and theories available in the literature.[5] In engineering and building science, there is no a widely accepted definition or rigid framework of what constitutes overheating or overheating risk. Most definitions are productivity, health or thermal comfort related.[6,7] Different definitions and metrics have been developed for different types of buildings (office, dwellings and others), calculation periods (part or total of the year), climatic conditions (heating or cooling dominated) and groups of people (vulnerable or not).[6,8] Metrics that assess comfort condition in a specific space and time for a specific typical user are not useful to assess the quality of a building. A new category of indices has been developed to fulfil this area. Long-term indices summarize in one cumulated value the thermal performance and the likelihood for discomfort (for this particular research for overheating) of a building over a period, taking into consideration of all spaces.

Long-term overheating indices are widely used for optimization of building elements and control strategies during the design phase and the long-term assessment of indoor conditions in existing buildings. Pane and Schnieders[9,10] used static indices to assess the impact of different thermal masses and glazing units in terms of summer overheating for dwellings. Grigon Masse et al.[11] and Di Perna et al.[12] used dynamic discomfort indices to optimize their cases during the cooling period. Attia et al.[5] and Carlucci and Pagliano[13] have used long-term metrics as objective and constraint functions for optimization.

Researchers and designers use different overheating metrics because they follow different models or comply with different regulations and standards. As a result, there is no common ground for generalization, intercomparison and final concordance of their outputs and conclusions. The main objective of this paper is to quantitatively compare and correlate (statistically investigate the relationship) the results of seven well-documented and widely used long-term overheating indices on four different representative dwellings and characteristic climatic conditions of central Europe (Denmark, the UK, Austria and South France). Different renovation steps and passive cooling strategies were applied on these case studies creating 66 variants for comfort assessment. Optimized 'best' comfort solutions, calculated by different overheating metrics, would be comparable on common scientific ground. In addition, potential quantitative relation of these indices would simplify the analysis conducted during the optimization process of the design or during the long-term comfort evaluation process for existing buildings. The use of different case studies and climates would allow the generalization of results for temperate climates (statistically significant), independent of climatic conditions, building geometries and types. This study also includes an inventory of the most widely applied overheating index for the long-term comfort assessment of the highly efficient renovated houses, based on literature and European standards and regulation reviews. The research extends evidences of previous research projects by comparing results from different climatic conditions and building geometries, always on residential buildings. In addition, this research offers inputs and quantitative data to the ongoing discussion conducted in Europe for the revision of these standards, which refer to the long-term assessment of indoor quality of buildings (expected in 2017).

The case studies of this paper were simulated as 'free-running' single-family houses (accept overheating) without active cooling systems. Overheating incidents were calculated not only during the cooling but also during transition periods. Regulations generally accept minimum deviation for overheating. Compliance with regulations of each country is out of the scope of this research. These analyses were conducted with the use of an internationally validated energy performance dynamic engine and widely accepted calculation methods and tools. The statistical analysis was carried out with the use of the R package.

Background

The literature shows more than 70 indices and metrics (mostly for summer overheating) that have been collected and analysed over time.[6,14] There is a great amount of theories and models in the literature, describing the relationship between certain conditions and human perception. Long-term metrics numerically cumulate in total the comfort assessment of the indoor space of a building in total over a long period. Long-term indices can be calculated either by monitored (existing building) or simulated data (for non-occupied buildings or during the design phase). For partly occupied or recently occupied spaces, extrapolation techniques give qualitative results and conclusions.[8] The most widely applied long-term overheating indices, which refer to 'free-running' (non-mechanically cooled) naturally ventilated residences, are described and calculated below for the fulfilment of objectives of this research.

The Chartered Institution of Building Services Engineers (CIBSE)[8] have proposed guidelines and overheating criteria based on fixed set points and thresholds (static indices), specified assessment periods and weather data. CIBSE guidelines[8] were reconsidered deeply in 2006 (Guide J) and totally in 2013 (Technical Memorandum 52). The latter guidelines for naturally ventilated buildings were based on the adaptive thermal comfort theory and aligned with the existing European standards and regulations.[15] The overheating indices of these guidelines are used widely in Europe.

The International standard, ISO 7730:2005[16] and European standard, BS EN 15251:2007[15] have proposed long-term discomfort indices and acceptable deviation ranges based on Fanger's and adaptive thermal comfort models. Fanger's models and adaptive theory have been analysed and revised by many researchers in the past, and they are the core models and methods for new European indoor assessment standards as well.[17,18] Residences include zones with different comfort requirements and less anticipated activities. In addition, there are high possibilities for thermal adaptation in residences through clothing (rate of heat loss), metabolic rate (activity level) differentiation, and environmental control (window opening, use of blinds or fans).[5,17] As a result, long-term discomfort indices based on the adaptive comfort theory are suggested for naturally ventilated (non-mechanically cooled) residential buildings (dynamic indices). Different versions of the adaptive theory have been developed over time.[6] The differences referred to the calculation period, the numerical characteristic of the regression model and the temperature applicability range.[5] In this paper, the European adaptive method has been analysed and used for the comfort assessment. All the metrics analysed below depend on the way indoor temperature is calculated.

Percentage of hours over a fixed temperature threshold

Four overheating metrics of this analysis belong to this category of indices. These indices refer to fixed temperature benchmarks. The examined thresholds are 25°C, 26°C, and 28°C respectively. These indices have been used on many research projects, which assess overheating conditions on housing, in the past.[19–22] The first two indices refer to the same 25°C threshold (equations (1) and (2)). The first index calculates the percentage of hours over the set point during the occupied and non-occupied hours (all day). The second index calculates the percentage of hours over the set point during only occupied hours.

The last two indices refer to the 26°C and 28°C thresholds only during occupied hours (equations (3) and (4)). The 26°C threshold for the whole building is used in many countries for overheating comfort assessment without the categorization of buildings to mechanically cooled or non-mechanically naturally ventilated. The use of this overheating benchmark is based mainly on the Fanger's theory. The acceptable deviation overheating ranges differ from country to country. In the CIBSE guidelines, these indices refer to specific rooms and assessment periods.[8] The use of these indices for this analysis is extended to all year and for the total building.

The formulas are presented as equations (1) to (4) below

$$F\_25\_A = \frac{\sum_{i=1}^{period}(wf_i * h_{i.all})}{\sum_{i=1}^{period} h_{i.all}} \tag{1}$$

$$F\_25\_O = \frac{\sum_{i=1}^{period}(wf_i * h_{i.o})}{\sum_{i=1}^{period} h_{i.o}} \tag{2}$$

$$F\_26 = \frac{\sum_{i=1}^{period}(wf_i * h_{i,o})}{\sum_{i=1}^{period} h_{i,o}} \tag{3}$$

$$F\_28 = \frac{\sum_{i=1}^{period}(wf_i * h_{i,o})}{\sum_{i=1}^{period} h_{i,o}} \tag{4}$$

Here wf_i is 1 if $T_i > 25$, 26 or 28°C, respectively; wf_i is 0 if $T_i < 25$, 26 or 28°C respectively; $h_{i,o}$ is an occupied assessment hour (all year), h; $h_{i,all}$ is an assessment hour (occupied or not, all year), h.

All the indices are calculated as percentages. The indices are assymetric and refer only to overheating incidents. In addition, they are not based on comfort models and comfort categories.[6] The indices are static, simple and easily understandable from non-technical users. On the other hand, these indices do not take into account the outdoor dry bulb temperature fluctuation and the adaptation process especially for dwellings. The indices depended on the calculation method for the indoor temperature and do not give information about the severity of the overheating problem.[8] The limitation of the assessed period underestimates the risk because they do not take into consideration the overheating incidents during transition months (high solar radiation in low angles).

Percentage of hours outside the comfort range

The index 'percentage outside the range-(POR)' calculates the percentage of occupied hours where the operative temperature is higher or lower (discomfort) than the upper and lower boundary of the calculated adaptive comfort model range (equation (5)). For renovation processes, category II is used (equations (6) and (7)). High level of expectation (category I) is recommended for buildings occupied by fragile users with special needs.[15] Without undercooling incidents, the index works as a long-term overheating index.

The formula is presented as equations (5) to (7) below

$$POR = \frac{\sum_{i=1}^{period}(wf_i * h_{i,o})}{\sum_{i=1}^{period} h_{i,o}} \tag{5}$$

Here wf_i is 1 if $T_i > T_{upper\ limit}$ or $T_i < T_{lower\ limit}$; and wf_i is 0 if $T_{lower\ limit} < T_i < T_{upper\ limit}$.

$$T_{limit} = 0.33 * T_{rm} + 21.8 \pm 3 \tag{6}$$

$$T_{rm} = \frac{\left\{\begin{array}{c} Ted_{-1} + 0.8 * Ted_{-2} + 0.6 * Ted_{-3} \\ + 0.5 * Ted_{-4} + 0.4 * Ted_{-5} \\ +0.3 * Ted_{-6} + 0.2Ted_{-7} \end{array}\right\}}{3.8} \tag{7}$$

Here T_{rm} is the running mean outdoor temperature, weekly assessed (°C); and $T_{ed\text{-}n}$ is the daily mean external temperature for the previous n day, (°C).

The index is dynamic, simple, symmetric, category based and with international consensus for use in 'free-running' and especially residential buildings.[15] The index does not offer information about the severity, but only for the frequency of the risk.[6] In addition, there is a discontinuity of the application of the index at the boundaries of the applicability range (10°C to 30°C).

Degree hours outside the comfort range

The index 'degree hours outside the range-(DHRS)' is similar with the previous one and based on the same adaptive comfort model and categories. Also, the index refers only to the occupied hours during the period. The index cumulates the number of degree hours where the actual (or calculated) operative temperature is higher or lower than the limit temperatures. The formula is presented as equation (8) below

$$DHRS = \sum_{i=1}^{period}(wf_i * h_{i,o}) \tag{8}$$

where $wf_i = abs[T_i - T_{limits}]$ if $T_i > T_{upper\ limit}$ or $T_i < T_{lower\ limit}$; and wf_i is 0 if $T_{lower\ limit} < T_i < T_{upper\ limit}$.

The index is comfort model based, assymetric and category dependent (Celsius-hours, not percentage). For the analysis, category II is also used. Without undercooling incidents, the metric works as long-term overheating index. The index offers information about the overheating severity of the indoor space.[6]

Difference between peak and annual average temperature

This index (DT) relates to the highest operative temperature indoors (simulated or monitored) with the annual averaged outdoor dry bulb temperature (°C). The index is climatic condition dependent. No information regarding the overheating frequency and severity of the indoor space may be extracted from this index.

Methods

Case studies

This research involves analysis of four different archetypes and climatic conditions (Figure 1), the UK (London), Denmark (Copenhagen), Austria (Vienna) and South France (Marseille). The chosen climatic conditions are representative of the temperate climates of central Europe.[23] The stock of these countries represents approximately 30% of the European Union building stock.[1] The case studies of Denmark, Austria and France represent more than two million dwellings of these periods. In addition, some of these examined countries have faced tremendous human losses from unusual high indoor temperatures in previous years.[4] In addition, buildings in central Europe will probably face unusual high temperatures due to effects of climate change in coming decades.

Reference buildings or archetypes established ought to reflect, as precisely as possible, the building stock (geometry, energy performance and construction type) of a certain country. The 'Typology approach for building stock energy assessment' (hereafter TABULA) project has a reference position regarding the characterization of representative residential buildings for a number of European countries. The single-family houses of this research were extracted from the TABULA project (Denmark, France) and from official reports of countries of the European Union (UK-DCLG; Austria-OIB).[24–26] The houses are from 1960s (Austria), 1970s and 1980s (France), one-storey (Denmark and France) or two-storey (UK and Austria) and detached or semi-detached buildings (UK).

The case studies have been constructed with the first or without energy regulations. The houses of these periods have high renovation potential in the following years.[2] The dwellings are heavy weight with limited insulation. Table 1 presents the thermal characteristics of the examined dwellings' envelopes.

Renovation steps

The increase of the efficiency of a building without the use of active or passive cooling methods and strategies

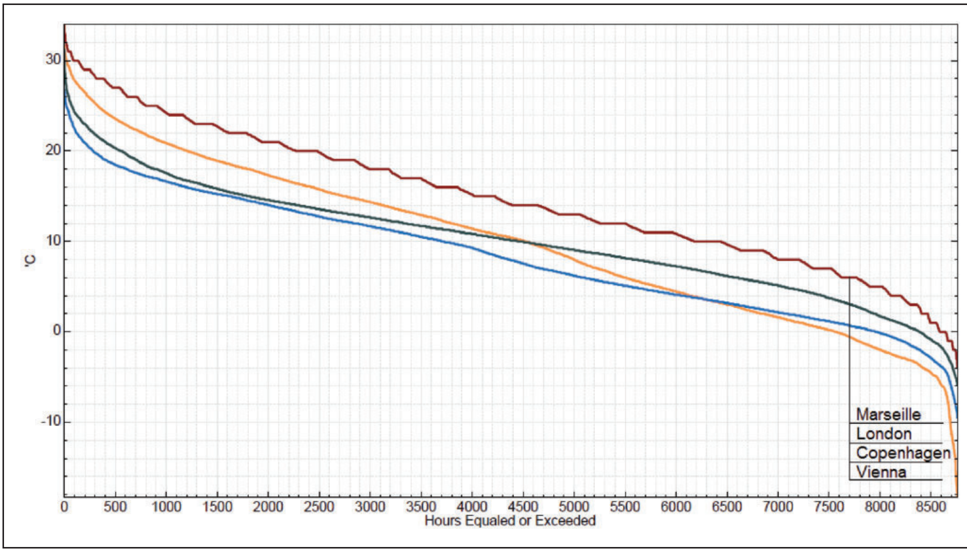

Figure 1. Accumulated outdoor temperatures (°C) of the examined locations (Marseille, London, Copenhagen and Vienna).

Table 1. Thermal characteristics (heat transfer coefficients (U), g value, infiltration (50Pa)) of the building envelope, for all the case studies and renovation steps (1: base case; 2: national renovation regulations; 3: nearly zero energy target).

a/a	U_{window} (W/m^2 K)-$g_{glazing}$	U_{roof} (W/m^2 K)	$U_{ext.\ wall}$ (W/m^2 K)	U_{floor} (W/m^2 K)	N_{50} (ach)
Austria (1)	3.0–0.67	0.55	1.20	1.35	3.0
Austria (2)	1.2–0.6	0.15	0.27	0.30	1.5
Austria (3)	0.8–0.5	0.15	0.15	0.15	0.6
Denmark (1)	2.7–0.76	0.45	0.45	0.35	5.0
Denmark (2)	1.65–0.7	0.15	0.20	0.12	1.6
Denmark (3)	1.2–0.6	0.15	0.20	0.12	0.8
France (1)	4.6–0.9	0.60	1.00	1.00	5.0
France (2)	1.5–0.7	0.22	0.43	0.43	1.4
France (3)	0.8–0.5	0.15	0.15	0.15	0.6
UK (1)	3.2–0.8	0.85	2.25	1.35	8.0
UK (2)	1.6–0.7	0.18	0.30	0.20	4.0
UK (3)	0.8–0.5	0.15	0.15	0.15	0.6

has been proven as a significant reason for the increase of the overheating risk indoors.[27] The four examined case studies were simulated as being renovated deeply and highly efficiently due to the national renovation regulation and a nearly zero energy target in steps creating different variants.[24–26,28] For the UK and Austrian cases, the renovation measures only include improvements to the efficiency of the building envelope (ceiling, external walls, windows, floor and airtightness; nine variants respectively). The national renovation benchmarks were used only as intermediate steps to energy efficiency. Checking the compliance with the highly efficient energy regulations of every country is outside the objectives of this research. For the Danish and French case, the renovation measures include not only improvements to the efficiency of the building envelope but also the use of passive cooling methods: shading systems and increase of the ventilation airflow

(23 and 25 variants, respectively). Three different shading systems were analysed:

- venetian blinds with high reflectivity;
- slat blinds with high reflectivity and
- fixed pergolas and awnings.

The movable shading systems were applied to all windows during unoccupied hours (Table 2). The increase of airflow was from the basic level of 0.5 ach, for minimum indoor air quality reasons, to 1.5 ach (in two equal steps). The airflow rates were applied constantly during all day.

Dynamic simulation

Analyses were conducted with the use of a highly sophisticated and widely applied building performance simulation engine, Energy Plus version 8.1. The models were designed with the use of a graphic user interface, Designbuilder version 4.2. The comfort assessments were conducted externally with the use of a self-developed office tool in Matlab.

The weather files (Figure 1) are updated and freely accessible with representative hourly data from the examined places.[29] The hottest climate of this research in terms of maximum outdoor temperature is the French climate, followed by the Austrian, the British and the Danish. The occupancy profile (Table 2) and internal loads (equipment and lighting: 2.4 W/m^2 (daily average), based on net floor area) reflect a five-member working family, occupying a house 77.4% of hours of a year.[27,30,31] The operative temperature calculation and the overheating comfort assessment of different case studies have been conducted based on the guidelines of the European standard.[15]

Regression analysis

All results of the seven examined long-term overheating indices of different variants were compared and correlated through linear regression analyses. Regression analyses were conducted with the use of R software (version 3.2.4). Tables 4 and 5 present the calculated regression models (best-fit) and the adjusted coefficients of determination (adjusted R^2) for all the examined pairs of indices (total data). In addition, Figures 2 to 4 present the adjusted coefficients of determination for every country separately based on the calculated linear regression models. Coefficient of determination is an indicator of how precise the regression line estimates the data points. The adjusted coefficient is a version of coefficient of determination that has been conformed to the number of predictors. Authors also included models with a second-order polynomial predictor term and logarithmic transformation of the response.

Table 3 presents the minimum and maximum values, the central tendency (mean and median), the standard deviation and the dispersion (coefficient of variation) of all the calculated long-term overheating indices for the 66 variants (univariate analysis).

Table 2. Weekly occupancy profile.

Occupation	Monday–Thursday	Friday	Weekend
Occupied	00:00–08:00, 16:00–24:00	00:00–08:00, 14:00–24:00	00:00–24:00

Results and discussion

This section describes and analyses the relationship (statistical comparison) of results of seven long-term indices with each other. Potential correlation of indices and metrics would simplify the analysis; these have been conducted during the design (optimization process) or operational (comfort assessment) phase of buildings. Comfort-optimized solutions calculated by different overheating metrics would be comparable on common ground. Static indices are totally understandable from users, but dynamic indices are closer to the human perception for comfort. Generally accepted overheating limits based on dynamic indices (e.g. 3 or 5% POR) from European standards or health reports may be transformed through these relationships to more simple metrics, different for every area.[15] The most significant statistical outputs of these analyses are presented below.

Dynamic long-term indices

This section describes the quantitative relationship of results of two dynamic long-term indices (POR and DHRS) with each other and with other static indices. Both dynamics indices calculate overheating incidents only during occupied hours (Table 2).

Table 4 presents all the calculated adjusted coefficients for the total of regression analyses. Coefficients of determination were calculated:

- without categorization of variants based on their origin and
- with categorization of variants based on their origin (climatic conditions and building geometries; four groups).

One model for every pair of indices and regression analysis (first order polynomial, second order

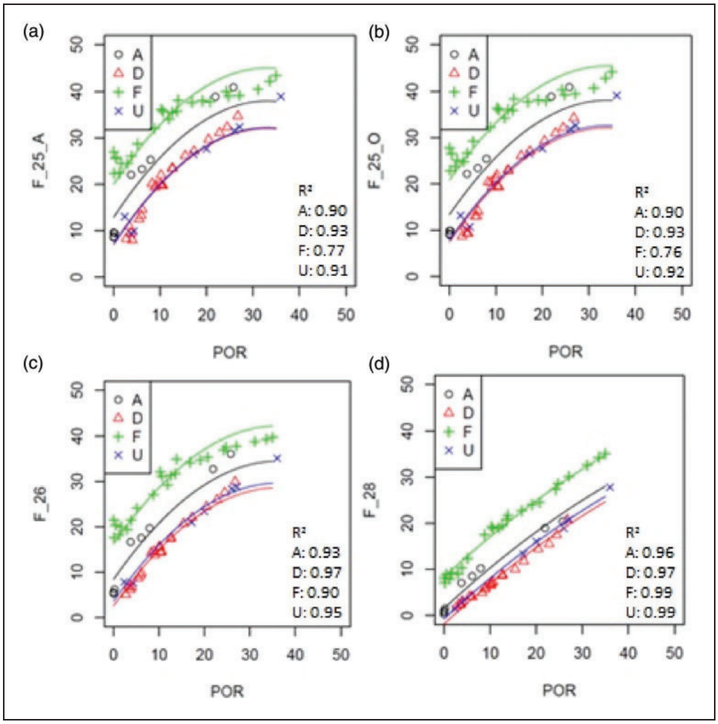

Figure 2. Best-fit models of the linear regression analyses of the POR overheating index (x–%) with the static overheating indices (y–%; (a), (b), (c) and (d)) for all the case studies and variants (categorization, A: Austria; F: France; D: Denmark; U: United Kingdom).

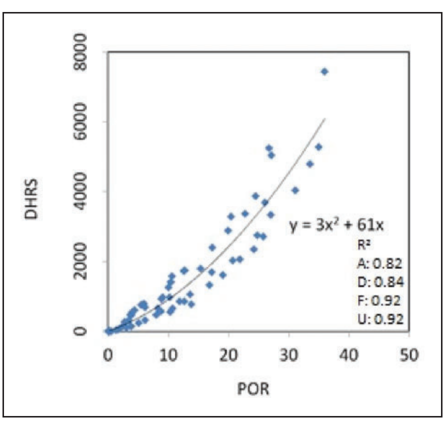

Figure 3. Best-fit model of the linear regression analysis of the POR overheating index (x–%) with the DHRS overheating index (y–°C h) for all the case studies and variants.

polynomial and logarithmic) was calculated also with the categorization of the data. This model is parametric (different interception points) based on the four examined case studies (Figure 2 and Table 5).

The best-fit models were calculated for every pair of indices for the total of the linear regression analysis (with and without categorization). The best-fit models are second-order polynomial equations for all the examined pairs of this section (Table 5). For all nine pairs of this analysis, the adjusted coefficients are significantly higher when we perform the categorization of data for the same regression analysis (Table 4). The best-fit models have adjusted coefficients from 0.84 to 0.99 (POR-F_28). The higher the reference benchmark of the static index is, the higher is the adjusted coefficient for both POR and DHRS indices. Table 5 also presents calculations of the standard errors (variance of the strength of the relationship). 'P-value' less than 5% gives statistical significant correlation between pairs of

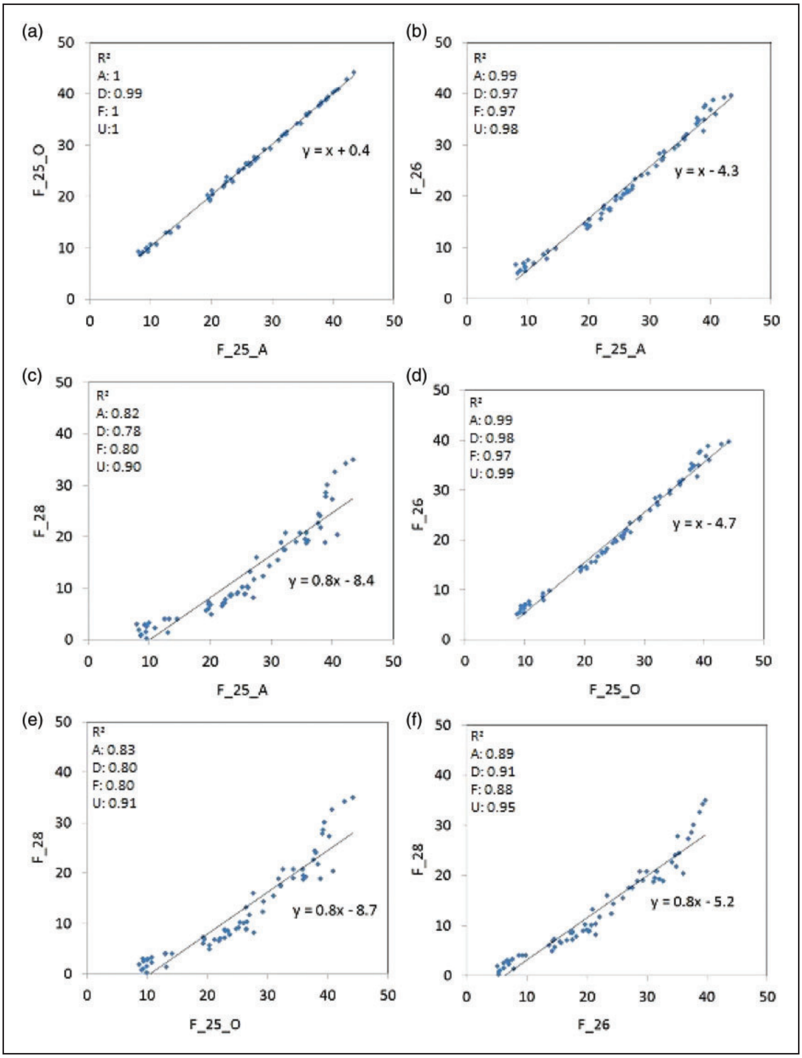

Figure 4. First-degree polynomial models of the regression analyses of the static overheating indices ((a), (b), (c), (d), (e) and (f)) with each other (%) for all variants (without categorization).

indices (total results of Table 5). Indices POR and F_28 create almost linear relationship with high adjusted coefficient. Adjusted coefficients are lower for the DHRS index compared with the POR index for the same correlation with static indices. Without categorization, the best-fit models are first- or second-order polynomial equations (not presented in this research). The adjusted coefficients are low to medium, from 0.38 to 0.75 (Table 4).

As a result of the statistical analyses, it is not possible to create a general relationship and a widely applied rule, independently of the examined climatic condition and dwelling, between the dynamic and static overheating indices. On the other hand, for every case individually, this relationship is clear with low variance and well described by second-order polynomial equations (Figure 2).

The recommended models (Table 5) may be used by local authorities and stakeholders for the development of 'local' relationships between static and dynamic indices (calculation of the interception point). Calculations for the development of representative relationships for local initiatives and regulations may be conducted on reference local buildings and updated climatic conditions or future data. The Danish and French cases (lower and upper lines on Figure 2) define the range and boundaries of the possible developed lines for the countries of central Europe. The French case shows the lowest adjusted coefficients of determination in three out of four graphs of Figure 2. In general, the adjusted coefficients of determination of the countries (Figures 2 to 4) are high (over 0.77) and with small differences amongst each other.

Table 3. Univariate analysis of the long-term overheating indices for all case studies and variants.

a/a	Indices	Min	Max	Mean	Median	Standard deviation	Coefficient of variation
1	POR	0.0	36.0	12.1	10.2	10.0	0.8
2	DHRS	0.0	7447.0	1485.6	860.1	1617.5	1.1
3	F_25_A	8.0	43.4	25.5	25.6	10.5	0.4
4	F_25_O	8.7	44.1	25.7	26.2	10.5	0.4
5	F_26	5.1	39.7	21.2	20.4	10.6	0.5
6	F_28	0.2	35.0	12.6	9.1	9.2	0.7
7	DT	15.3	30.5	22.2	22.0	4.3	0.2

Figure 3 presents the relationship of two examined dynamic indices with each other, without categorization. Long-term overheating indices originate from the same adaptive comfort theory directly related with each other (second-order polynomial model), independently of the referred case, with adjusted coefficient of 0.91. Taking into account the categorization of the data, the coefficient does not improve considerably. The correlation is even higher for overheating occurrences under 15% (POR). The Austrian case shows the lowest adjusted coefficient of determination (Figure 3).

As a result, designers, modellers and researchers may, with high statistical confidence, directly compare their conclusions and optimized solutions on common scientific ground, assessed by these two dynamic indices. The inclusion of both dynamic metrics to the standards and regulations is unnecessary. Overheating deviation limits (yearly based) for the DHRS index are suggested to be calculated based on the POR limits through the developed equation.

Table 4. Adjusted coefficients of determination of the linear regression analyses (with (*) and without categorization) for all pairs of indices.

x	y	First-order polynomial model	First-order polynomial model*	Logarithmic model	Logarithmic model*	Second-order polynomial model	Second-order polynomial model*
POR	DHRS	0.87	0.90	0.57	0.73	0.91	0.96
POR	F_25_A	0.60	0.88	0.51	0.75	0.60	0.92
POR	F_25_O	0.59	0.89	0.50	0.77	0.59	0.92
POR	F_26	0.63	0.93	0.53	0.80	0.62	0.96
POR	F_28	0.75	0.99	0.62	0.84	0.74	0.99
POR	DT	0.04	0.95	0.05	0.96	0.14	0.95
DHRS	F_25_A	0.36	0.78	0.30	0.66	0.39	0.84
DHRS	F_25_O	0.35	0.79	0.29	0.68	0.38	0.85
DHRS	F_26	0.38	0.83	0.32	0.71	0.41	0.89
DHRS	F_28	0.51	0.90	0.40	0.74	0.53	0.95
DHRS	DT	0.12	0.94	0.13	0.94	0.19	0.96
F_25_A	F_25_O	1.00	1.00	0.96	0.96	1.00	1.00
F_25_A	F_26	0.99	0.99	0.97	0.97	0.99	1.00
F_25_A	F_28	0.88	0.89	0.93	0.95	0.95	0.96
F_25_A	DT	0.05	0.94	0.06	0.94	0.05	0.95
F_25_O	F_26	0.99	0.99	0.97	0.97	0.99	1.00
F_25_O	F_28	0.89	0.89	0.93	0.95	0.95	0.96
F_25_O	DT	0.07	0.94	0.07	0.94	0.06	0.94
F_26	F_28	0.93	0.94	0.92	0.95	0.97	0.98
F_26	DT	0.07	0.95	0.06	0.95	0.06	0.95
F_28	DT	0.03	0.95	0.03	0.96	0.02	0.96

Table 5. Coefficients and standard error results of best-fit models of linear regression analyses (second-order polynomial) of dynamic indices with static indices (categorization; interception point based on the case study).

Indices (x, y)	x_local	I(x_local^2)	Denmark	France	UK	Austria
POR-F_25_A	1.517/	−0.02297/	−5.879/	7.129/	−5.708/	12.86/
	0.1308	0.004059	1.227	1.174	1.427	1.079
POR-F_25_O	1.456/	−0.02146/	−5.918/	7.453/	−5.432/	13.33/
	0.1289	0.003999	1.209	1.157	1.406	1.063
POR-F_26	1.438/	−0.01987/	−5.832/	7.815/	−4.804/	8.396/
	0.0939	0.002913	0.8806	0.8425	1.024	0.7743
POR-F_28	0.9257/	−0.004824/	−3.371/	6.769/	−2.228/	1.521/
	0.04338	0.001346	0.4068	0.3892	0.4731	0.3576
DHRS-F_25_A	0.008925/	−8.041e-07/	−6.804/	8.526/	−6.851/	16.13/
	0.0009289	1.614e-07	1.725	1.656	2.079	1.455
DHRS-F_25_O	0.008688/	−7.734e-07/	−6.897/	8.802/	−6.597/	16.47/
	0.0009035	1.57e-07	1.678	1.611	2.022	1.415
DHRS-F_26	0.009147/	−8.255e-07/	−7.122/	9.13/	−6.033/	11.41/
	0.0007692	1.337e-07	1.429	1.372	1.722	1.205
DHRS-F_28	0.007913/	−6.242e-07/	−5.597/	7.68/	−3.87/	3.419/
	0.0004673	8.121e-08	0.8679	0.8334	1.046	0.7319

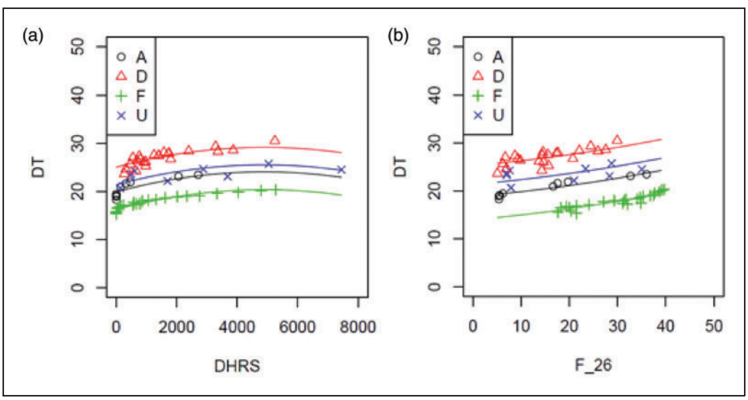

Figure 5. Best-fit models of the linear regression analyses of the DT overheating index (y–°C) with the DHRS (a) and F_26 (b) indices (x–°C h and %) for all the case studies and variants (categorization, A: Austria; F: France; D: Denmark; U: United Kingdom).

Static long-term indices correlation

This section describes the quantitative relationship of results of four static long-term indices with each other. Three out of four static indices calculate overheating incidents only during occupied hours (apart from F_25_A). All indices are in percentages.

The best-fit models are also second-order polynomial equations with coefficients of determination from 0.96 to 1.00. The adjusted coefficients are slightly higher when we perform the categorization for similar linear regression analyses. Without categorization and first-order linear regression analysis, the coefficients of determination are also high from 0.88 to 1.00 (Figure 4; indices F_25_O and F_25_A). The variance is insignificant for overheating fewer than 20% (F_28; Figure 4). First-order polynomial equations were preferred over second-order equations for these pairs of static indices without significant statistical penalty, for simplicity reasons.

The results show that it is possible to create a general and widely applied relationship between static overheating indices independently of the case study and climatic condition. The recommended equations (Figure 4) show low variance and high adjusted coefficients especially to medium and low values of overheating. The French and Danish cases show the lowest adjusted coefficients of determination in three out of six graphs of Figure 4.

A number of indoor quality guidelines and regulations suggest overheating deviation limits based on fixed benchmarks (static) either based on percentages of occupied hours or direct numbers of hours. The Danish regulation suggests two consecutive benchmarks as limits for indoor overheating risk assessment (100 h over 27°C and 25 h over 28°C).[28] The recommended models statistically predict the maximum average indoor temperature of the dwelling from the accumulated values on lower thresholds (e.g. if 10.5% of the occupied hours have an indoor temperature over 25°C, then the maximum average temperature of the dwelling is lower than 28°C (0%), Figure 4). As a result, this double overheating check as suggested by a number of regulations is unnecessary. The static long-term overheating indices refer to the total dwelling, averaging the zone temperatures. Local rooms may face overheating problems more often than the total house.[17]

A number of regulations also suggest different occupancy profiles for the overheating assessment of different building types. These suggestions are not always precise or accurate. The results of the overheating indices F_25_O and F_25_A (similar benchmark but different calculation hours) are directly related with the first-order equation with a high coefficient of determination (Figure 4). From the equation, it is possible the overheating assessment to be extrapolated from the occupied hours directly to all day and opposite. The coefficients of the model ($a = 1$ and $b = 0.4$) refer to this temperature benchmark and occupied schedule (77.4% occupied). Different overheating static indices and different occupancy schedules would create different extrapolation coefficients.

The relationship of the DT index with the other static and dynamic indices gives models with adjusted coefficients close to zero (from 0.0 to 0.2) without categorization (Table 4). With the categorization of variants, the adjusted coefficients are from 0.93 to 0.96. The reason for this large discrepancy is that this overheating index is highly correlated with the outdoor climatic condition, by definition. The inclination (slope) of the calculated models for all the combination of indices with DT index is close to zero (horizontal lines, Figure 5). The DT overheating index remains almost constant for different values of the other overheating indices (dynamic or static). The use of this overheating index is not recommended for optimization purposes of energy renovated dwellings during the design phase and long-term comfort assessment of an existing one.

Conclusions

This paper has quantitatively compared (investigation of the relationship), contrasted and statistically analysed seven widely used and well-documented long-term overheating indices and metrics. These metrics have been applied on four different 'free-running' representative dwellings under energy renovation in four characteristic temperate climates of central Europe.

From the analysis we may conclude that it is not possible to develop a widely applied relationship between the dynamic and the static overheating indices for general use. However, for each case individually, this relationship between dynamic and static pairs of indices is clear, with low variance and well described by second-order polynomial equations. Generally accepted overheating deviation limits based on dynamic indices may be transformed through these relationships to more simple metrics, different for every area. The Danish and French cases define the range and boundaries of the possible developed lines for countries of central Europe.

In addition, dynamic long-term overheating indices originate from the same adaptive comfort theory directly related (second-order polynomial equation), independently of the referred case, with high adjusted coefficient of determination. The inclusion of both dynamic metrics to standards and regulations is unnecessary. The use of the DT overheating index is not recommended for optimization purposes of energy renovated dwellings during the design phase and long-term comfort assessment of an existing one.

The relationships between static indices are linear (first-order polynomial) with high confidence and case independent. As a result, double overheating thresholds as suggested by a number of regulations are unnecessary. Overheating indices with similar benchmarks but different calculation hours directly related (first-order polynomial) with high adjusted coefficient of determination (possibility of extrapolation). Different overheating static indices and occupancy schedules would create different extrapolation coefficients for the model.

More research with different occupancy profiles, temperature thresholds, climatic conditions and building types (also building sizes) also to hotter climates or less renovated dwellings has to be conducted in the future for the verification of the recommended models and conclusions. Verification of the models with real indoor temperature data from residential buildings on temperate climates is also suggested. Similar analysis may be conducted also for long-term discomfort indices including also undercooling incidents.

Authors' contribution

This study was organized by TP, and PH and KD were the scientific advisors of this work. All the data analyses were performed by TP and MA, and the manuscript was prepared by TP. All the revisions were made by TP, MA and PH. All the authors contributed equally in the preparation of this manuscript.

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The authors are presently contributing to the ongoing work for investigating and maturing ventilative cooling as an attractive and energy-efficient solution to avoid overheating of both new and renovated buildings within the International Energy Agency EBC Annex 62: Ventilative Cooling.

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Appendix III

Article 3

Psomas T, Heiselberg P, Lyme T, Duer K. Automated roof window control system to address overheating on renovated houses: Summertime assessment and intercomparison. Energy and Buildings Journal 2017;138:35-46.

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Automated roof window control system to address overheating on renovated houses: Summertime assessment and intercomparison

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A B S T R A C T

Major and deep energy renovations on residential buildings are expected in Europe over the next several years. The current developments towards nearly-zero energy houses in building efficiency have increased the overheating occurrences indoors. For house users summer thermal discomfort is an unknown challenge that they have not faced in the past. The objectives of this study is to highlight the problem of overheating in energy renovated dwellings in temperate climates and to investigate the ability of automated roof window control systems to address the risk during the peak summer period. The assessment of the indoor environment was conducted in a typical two-storey house, close to Copenhagen. Both dynamic and static criteria were used to carry out risk evaluation.

The assessment of the monitored data of the house verifies the fact that active and passive ventilation and shading systems, if manually controlled, cannot guarantee high quality indoor environment. The use of automated roof window control system may significantly decreases the overheating risk without any significant compromise of the indoor air quality. The developed system is analyzed in detail. Suggestions for future work are also proposed.

1. Introduction

Denmark has more than 1.5 million residential buildings in use and the majority of them are single-family detached houses [1,2]. During the 1960s and 1970s, approximately 440,000 single-family dwellings were built without or with the first energy regulations [3]. Buildings constructed before 1980 are responsible for 75% of the total energy use of the sector [4]. In spite of many years with demanding energy requirements established by the Danish building regulations (BR 2006, BR 2010, BR 2015), the existing building stock still offers a colossal potential for energy savings [5].

Danish regulations suggest cost-effective saving solutions and measures for renovation processes related mainly with the increase of the airtightness and insulation levels of the buildings [5]. The strong interest to the extended heating season may lead the stakeholders and designers to pay inadequate attention to the indoor thermal quality of the residential buildings during the hotter months (simplified methods, averaging the need in time and space; [6]). The decrease of the infiltration rate of the buildings, the increase of the outdoor temperature and solar radiation and the large window surfaces will result in considerable indoor thermal discomfort [7]. Deeply renovated houses have a tendency to overheat, even in the mild summers, and are more sensitive to extreme thermal conditions than older houses [8]. Various researchers have documented the overheating risk in high efficient new or renovated houses without active cooling systems of central and west Europe [9–12]. In many post-occupancy evaluation comfort studies and building parametric simulations, elevated temperatures have also been documented even in climatic conditions of north Europe [13–17]. Analytical health research concludes that discomfort conditions for extended periods of time cause serious impact and consequences to the environmental thermal quality of the space and result in a very important increase of vulnerability, adverse health effects and mortality [18,19].

Important experimental (real buildings and test cells) and theoretical research have shown that passive cooling methods, like ventilative cooling and solar shading, provide excellent indoor

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Table 1
Heat transfer coefficient (U) and g value of the elements of the case study (both floors).

	Floor-ground floor	External wall-ground floor	Ceiling-ground floor	Internal partition-ground floor	External wall-upper floor	Roof	Internal partition-upper floor	Roof window (glazing)-(g value)	Façade window (glazing)-(g value)
W/m^{2}K-(no units)	0.19	0.37	0.21	2.48	0.16	0.11	0.32	1.10–(0.63)	2.70–(0.75)

quality both in terms of thermal sensation and air quality, with low energy use [20]. External cool air may remove internal and solar thermal loads as well as increase ventilation rates and, thereby, widen the comfort acceptability [21]. Occupants in naturally ventilated spaces suffer less from "sick building" syndromes [18]. Ventilative cooling through openings during night may prove very refresh and efficient in different types of buildings [22]. The use of night ventilation may reduce the next day peak indoor temperature up to 3 K and the cooling load on residential buildings up to 40 kWh/m^2/year [20,23]. A list of 26 buildings in operation with ventilative cooling principles and control strategies is available in Ref. [21].

In passive nearly zero energy houses the occupant's behavior, preferences and attitudes become critical [24]. User behavior has identified to be crucial element for successful performance and effectiveness of ventilative cooling strategies [21]. Wallace et al. concluded that 87% of the total air change rates of buildings are related to the user's behavior, mainly on natural system use [25]. Kvistgaard et al. and Bekö et al. conducted air change rates measurements in 16 similar Danish dwellings and 500 bedrooms respectively, and their main conclusion was that occupancy behavior is responsible for these large discrepancies in energy and comfort results [26,27]. Literature reviews on occupant's window opening behavior (models and factors) are presented in detail in Refs. [28–30]. The majority of this analysis refers to office buildings. Window behavior models for residential case studies are presented in Refs [31,32]. Both models refer to temperate climates, taking into account indoor and outdoor environmental parameters and indoor air quality data and deriving from large amount of field test studies.

For house users of temperate climates overheating discomfort is an unknown challenge that they have not faced in the past. The occupants do not know how to efficiently diminish the risk and their behavior might instead increase it [21]. Automated control systems integrated in window configurations, hereafter called "window systems", are already implemented widely in commercial buildings [33]. Window systems are able to communicate with each other and to return control to the user [34]. Simultaneously, the systems inform the user and give advices about how to achieve comfort conditions with the minimum energy use. The dwellings of the northern temperate climates typically ventilate and cool their spaces by manual window opening supported by mechanical ventilation systems [21]. The application of the window systems in dwellings is still limited [33]. Window systems oriented on building limitations and users' needs provide compelling energy savings for conditioning and ventilation [35,36].

The extensive study reported herein aims to examine and highlight the problem of overheating and thermal discomfort in energy renovated dwellings in temperate climates and to investigate the ability and effectiveness of window systems with integrated straightforward heuristic control strategies based on real time monitoring of the indoor and outdoor environmental parameters, in order to address the risk during the peak summer period and to maintain or improve the indoor air quality and environment of the spaces. This research work directly compares the manual control against the automated control of the window configurations, in terms of ventilative cooling effect and overheating risk for a real case study (in use) in temperate climate and for a complete cooling period.

The thermal and indoor air quality assessments and evaluations were conducted in a 1930s two-storey dwelling in use, close to Copenhagen, that was not prone to overheat before the deep renovation of the upper floor. The evaluation is based on an analytical monitoring campaign started after the renovation works. Indoor environments is compared in terms of thermal discomfort and indoor quality for two consecutive, almost identical summer periods (June, July and August); one without the system implemented and one with the system installed at the roof windows of the upper floor. Indicators of the indoor air quality used the carbon dioxide concentration and the relative humidity. Both static and dynamic thermal discomfort and overheating criteria in room, floor and house levels (possible only in 2016) were used to carry out risk evaluation. The developed window system is presented and analyzed in detail. The input user values for the different functions of the system and how these values potentially affect the indoor environment are analyzed and highlighted. A supplementary objective of the research is the investigation of the inconsistencies and deficiencies, which arise from the use of different methods at the assessment analysis.

2. Description of the case study

The case study is a typical yellow brick single-family house (Fig. 1a) located in Birkerød, a suburban area northern of Copenhagen. It was built in 1937 and it is a two-storey detached building with a concrete basement. The gross area and the internal net volume of the house are 172.4 m^2 and 363.3 m^3 respectively. The owners of the house are a typical working family, with two parents and two children. The house is not shaded apart from a large high tree (double in height) in a small distance from the south façade.

Table 1 presents the thermal characteristics of the different elements of the case study for both floors. In 2006, the ground floor was insulated and gas heating system for both floors (additional wood stove) was installed. The insulation of the external wall of the ground floor (before 2006) was performed internally (foam inside the bricks). In 2013, the roof was completely rebuilt with additional internal insulation and vapor barriers [37]. Finally in late 2014, the family has finished the deep renovation of the upper floor (Fig. 1b and c), adding new wooden screed flooring with additional insulation and installing eleven pivot roof windows (nine with electrically driven actuators and motors; (Fig. 1d)). The roof windows were installed in the three bedrooms, the bathroom and the corridor. All the roof windows, apart from those of the corridor, have integrated automated internal shading systems-blackout blinds and the south roof windows have also additional external shading systems-awnings (dark colored). Façade windows are double side-hung wooden windows with double glazing from the middle of 1990s. In the middle of the south façade of the first floor there is a small balcony (overhang). All the façade windows and balcony door have integrated light-white internal shading systems (curtains, roller blinds or venetian blinds; Fig. 1d). The external door and the door to the basement are wooden. Table 2 presents the areas of the openings and the window-to-wall ratios for all the orientations of the case study. Table 3 presents the window-to-net floor area ratios for all the monitored rooms of the case study.

Balanced mechanical ventilation system was installed with inlets and outlets on the ground floor (living room and kitchen),

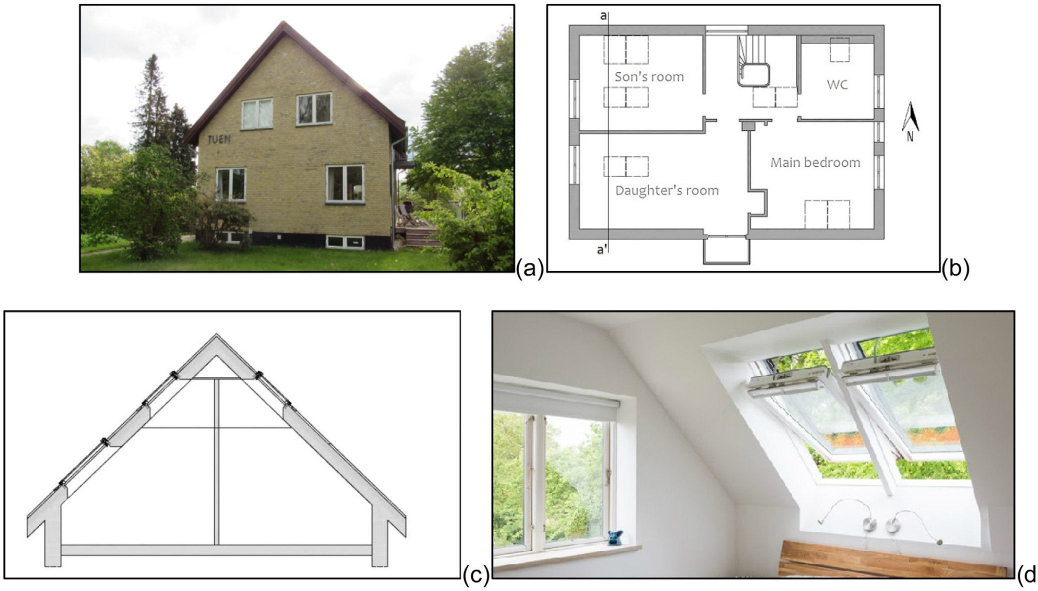

Fig. 1. West view of the case study (a), floor plan of the upper floor (b), a-a' section of the upper floor (c) and roof window configuration with shading system and motors (main bedroom; d).

the three bedrooms and the bathroom of the upper floor. The typical airflow rate of the mechanical ventilation system is 0.5 ach for indoor air quality reasons and is controlled by temperature set points (86% maximum heat recovery efficiency and 0.9 ach maximum airflow rate).

The control of the façade windows and shadings systems of both floors is manual. Façade windows and shading systems of the upper floor during the summer of 2016 was completely closed and open respectively, based on the suggestions of the research team (not recorded). Control of roof windows (opening and shading) during the summer of 2015 was manual supported by an electronically assisted system based on time (purge ventilation for 15 min on demand, 4 times per day). The developed window system (Section 4) was installed in the dwelling before the summer period of 2016. Connected with the window system are only the nine roof windows of the upper floor and the five zones, the three bedrooms, the WC and the corridor (Fig. 1b). The mechanical ventilation system was closed (start of June 2016). Rain sensors are pre-fitted in every roof window. The roof windows close automatically in case of rain.

3. Methodology

3.1. Climatic conditions

The climate of the examined area is a typical temperate climate of northern Europe (Cfb on Köppen-Geiger classification, fully humid-warm summer; [38]). Solar radiation, precipitation and wind speed information for the summers of 2015 and 2016 was taken from the closest weather station of the Danish Meteorological Institute, Sjælsmark, which is located 3.7 km away from the study site. Fig. 2 presents the outdoor temperature (per month and in total), the wind speed (in total), the accumulated global radiation (horizontal surface per square meter) and the accumulated precipitation of the examined area for the summers of 2015 and 2016 respectively. In terms of outdoor temperature, the 2016 summer period was slightly hotter on average (June and July) than the same periods of 2015 (Fig. 2a). The peak temperature was in July for 2015 and in August for 2016. Wind speed intensity, comparing median and peak values, in 2016 was lower than in 2015 (Fig. 2b). Accumulated global radiation at the end of the monitoring period was slightly lower for the summer of 2016 (Fig. 2c). During the whole examined period, these lines almost coincide and the differences are negligible. The raining hours for 2016 were 188 and 181 for 2015 (no possible window opening). Outdoor temperature and solar radiation affect the indoor conditions and the risk of overheating. Wind speed intensity affects the natural ventilation and ventilative cooling processes. In general, the weather data indicates that occupants of the examined dwelling experience almost identical outdoor conditions for both summer periods.

Table 2
Opening area and window-to-wall ratio for the different orientations of the case study.

	North	South	East	West
Openings (m^2)	12.3	16.1	7.1	7.3
Window-to-wall ratio (%)	13.7	17.9	19.0	19.6

Table 3
Window-to-net floor area ratio for the different monitored rooms of the case study.

	Main bedroom (south-east)	Daughter's room (south-west)	Son's room (north-west)	Corridor (north)	WC (north-east)	Living room (south-west)	Kitchen (north-east)
Windows-to-net floor area ratio (%)	30	32	36	31	28	34	26

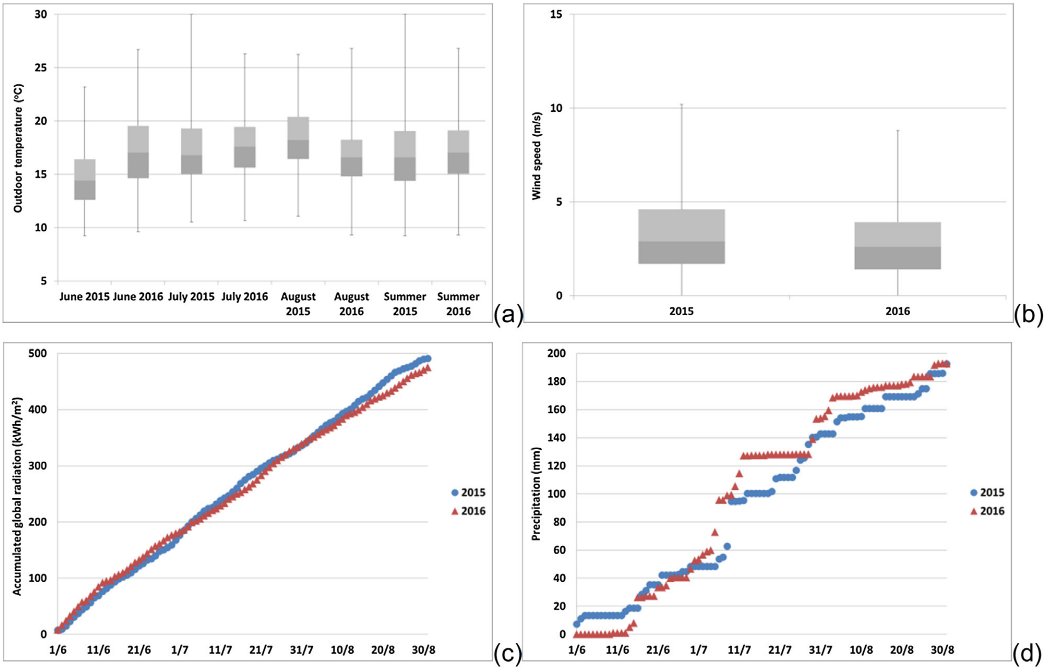

Fig. 2. Comparison of outdoor temperature (a), wind speed intensity (b), accumulated horizontal global radiation (c) and precipitation (d) of the examined area, during the summer periods of 2015 and 2016.

Table 4
Range and accuracy levels of the sensors of the environmental parameters.

	Temperature (°C)	Relative humidity (%)	Carbon dioxide concentration (ppm)
Range	0~50/−40~65 (outdoor)	0~100	0~5000
Accuracy	±0.3	±3	±50 or 5%

3.2. Monitoring campaign

The upper floor of the house (Fig. 1b) was monitored continuously from 19th of May 2015. The main rooms of the ground floor (living room and kitchen) were monitored from 18th of May 2016. The monitoring campaign is still in progress. For every room the temperature, the carbon dioxide concentrations and the relative humidity (internally) has been monitored as well as the temperature and relative humidity (externally) with 5-min time steps.

Sensors were encapsulated inside plastic silver boxes. The size of the sensors was minimized to not disturb occupants in their daily life. In well insulated buildings air temperature is likely to be a realistic assumption for operative temperature [12]. The outdoor sensor was installed, totally protected from direct solar radiation, at the south east part of the house under the extension of the wooden roof. The indoor sensors were installed to avoid direct solar radiation and heat sources (appliances, radiators, ovens and others), at the center of the rooms in bed height. For the living room and kitchen, the sensors were installed approximately at the internal half-height of the room. The height is typical for the head region of seated occupants and the middle region for occupants on standing activities [9]. Missing data was interpolated from monitored data of adjoining rooms. Erroneous data was extracted from the analysis. The accuracy values of the sensors fulfill the requirements of ISO 7726 standard (Table 4; [39]).

3.3. Thermal comfort and overheating assessment

The scientific literature holds no widely accepted definition of what constitutes overheating in buildings and describes more than seventy applicable indices worldwide [19,40]. The majority of the definitions are either thermal comfort related or they are based on health evidences [41]. During the last decade, a new type of indices has been used describing in one number the long-term thermal discomfort conditions of spaces or buildings [40,41]. It is used widely for the operational assessment of indoor conditions of existing buildings. In dwellings there are multiple ways for thermal adaptation through clothing and activity differentiation and environmental control (use of openings, blinds and fans; [42,43]). Long-term indices based on the dynamic adaptive comfort theory are used for naturally ventilated, non-mechanically cooled residential buildings [44]. Evaluation tools based on the dynamic adaptive theory reflect the occupant's perception and experiences for thermal comfort more precisely.

This study work uses two well documented and widely applied methods for the evaluation of the overheating risk and discomfort conditions during the peak cooling period. The first index "percentage outside the range" or "POR" refers to the dynamic adaptive comfort theory [45]. The index calculates the percentage of hours in which the operative temperature is higher or lower than the upper or lower boundary of the adaptive comfort model (Eq. (1) and (2)). The house is assumed to be occupied during all day for both summer periods [46].

For renovated cases, category 2 is employed (Table 5). Higher level of expectation (category 1) is recommended for dwellings occupied by fragile and sensitive users with special needs. For total floor or building assessment the indoor temperatures of the spaces weighted, in net volume terms, in one value. European standards

Table 5
Limit value of indoor operative temperature for the different categories of the standard [45].

	Category 1	Category 2	Category 3[a]
Upper limit	+2	+3	+4
Lower limit	−3	−4	−5

[a] In category 4 belong the indoor temperatures above or below the other categories.

Table 6
Indoor air quality limits for carbon dioxide concentration (ppm) and relative humidity (%) for the different categories of the standard [45].

	ΔCO_2 concentration (ppm above outdoors)	Relative humidity (%)
Category 1	380	50
Category 2	550	60
Category 3[a]	950	70

[a] In category 4 belong the values above the other categories.

suggest acceptable deviation length 3% or 5% for every examined category (5% is employed for this work study; [45]). Table 5 presents the upper and lower limits of Eq. (2) for all the categories.

$$T_{rm} = (T_{ed-1} + 0,8 \times T_{ed-2} + 0,6 \times Te_{d-3} + 0,5 \times T_{ed-4} + 0,4 \times T_{ed-5} + 0,3 \times T_{ed-6} + 0,2 \times T_{ed-7})/3.8 \quad (1)$$

$$T_{i,op.max/min} = 0.33 \times T_{rm} + 18.8 \pm \text{categoryrangelimit} \quad (2)$$

$T_{i,op.max/min}$: limit value of indoor operative temperature (°C)
T_{rm}: running mean outdoor temperature (°C).
$T_{ed\text{-}i}$: is the daily mean external temperature for the previous days (°C)

Different static criteria are used extensively in the literature to assess overheating risk in houses [19]. To evaluate the risk of overheating for existing buildings, the Danish regulations suggest fixed threshold temperatures for critical rooms, independently of the outdoor conditions and categories. The overheating limits are 100 h over 27 °C and 25 h over 28 °C [6]. In this study, all the monitored rooms of the upper and ground floors (possible only in 2016) are assessed by these criteria. This method is simple and easily understandable and communicable to non-technical users.

3.4. Indoor air quality assessment

The indoor air quality assessment and evaluation in terms of carbon dioxide concentration and relative humidity is conducted based on fixed thresholds (Table 6). European standards accept 5% maximum acceptable deviation length for category 2 [44,45]. All rooms were assessed also based on the suggestions of the Danish building research Institute (SBI), as far as the maximum acceptable relative humidity of the spaces; less than 1% of the time over 75% [47]. Benchmarks suggested for relative humidity do not apply to residential buildings [45]. The use of these thresholds to this research is for intercomparison reasons between the different summer periods.

4. Description of the window system

Window systems with rule based control will be the industry standard for many years [48]. Heuristic control strategies based on “IF (condition)-THEN (action)” were found to be ideal for window systems of naturally ventilated and cooled buildings [49]. Martin et al. (1996) calculated that complex algorithms and control strategies for ventilation in many cases do not perform better than simple ones [50]. Schulze et al. (2013) concluded that the settings of the parameters of the strategies in many cases are more important than the control strategy itself [51]. Advanced window systems are cost-inefficient for residential buildings, depended on the fidelity of the model and seem to be complex for the users.

The control system of the window in this research work has integrated three functions for user activation:

1 Cooling (Ventilative cooling)
2 Indoor air quality
3 Shading

for the three different occupancy states of the user: non-occupied (not used), occupied and night (functions described below). Occupancy state changes by the user or by time (morning and night time) and referred to a specific space-zone. The system is accessed by a mobile application, developed specifically for the research project. Through this mobile application, the user may decide for every zone separately which functions to be active for every occupancy state (possible simultaneous activation). The user has the possibility also to choose and differentiate the set points for 4 parameters and the control evaluation period of the algorithm (Figs. 3a and 3b):

1 Indoor natural ventilation cooling temperature, set point range: 18–30 °C
2 Indoor temperature for shading, set point range: ±3 °C relative to natural ventilation cooling temperature
3 Carbon dioxide, set point range: 400–2000 ppm
4 Relative humidity, set point range: 50–90%
5 Time interval for control action, range: never, 10 min-4 h

In addition, the user has the possibility to check the stored values of the environmental parameters of the current day for every zone separately. Special signals for critical environmental values are show up for informative reasons. Standards suggest that giving to the users the control of their environment the level of their satisfaction is increased [44]. The user has the possibility to override (increase, decrease, close or open) or to deactivate the system at any time of the day.

1) Cooling function (Fig. 3a)

Windows open, when the outdoor air is colder than the indoor zone air and the indoor zone temperature over the natural ventilation cooling temperature set point, incrementally (5 integrated steps, 10%/25%/50%/75%/100% of the window actuator). The maximum accepted temperature difference between outdoor and indoor temperature is 10 °C. After a time interval if the examined environmental parameter is higher than the previous value, opening steps to the next increment (if not opening stays unchanged).

2) Indoor air quality function (Fig. 3b)

Windows open, when the carbon dioxide concentration or the relative humidity percentage is over the set point (also outdoor absolute humidity plus an error factor is lower than the indoor), incrementally (similar steps). Between the two examined factors, carbon dioxide concentration is set as the most important factor for window opening (indoor air quality). The maximum accepted temperature difference between outdoor and indoor temperature is 10 °C for colder outdoor conditions and 5 °C for hotter outdoor conditions. For parallel use of cooling and indoor air quality functions, the windows follow the cooling function (in priority) for indoor temperatures over the natural ventilation cooling set point temper-

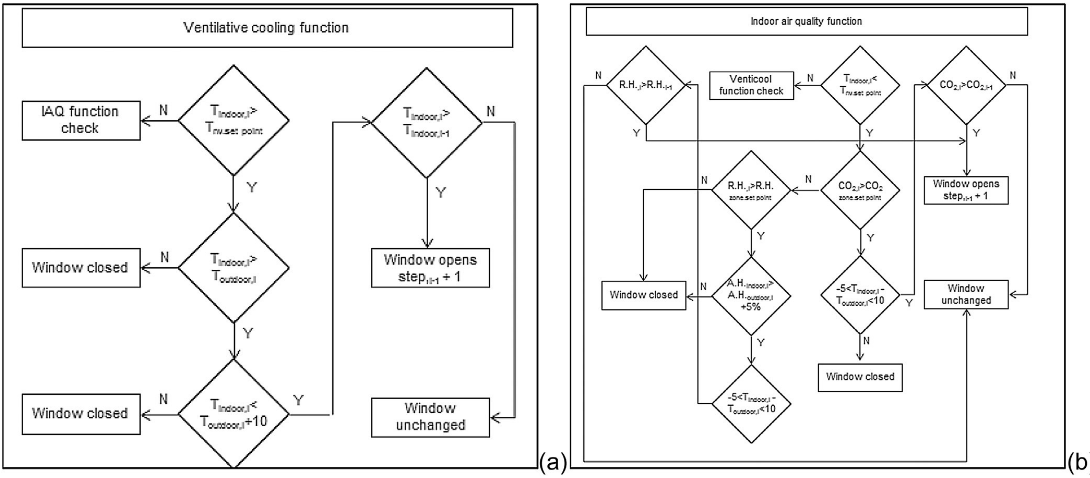

Fig. 3. Ventilative cooling (a) and indoor air quality (b) algorithms integrated to window system. (T: stands for temperature, $T_{nv,setpoint}$: stands for natural ventilation cooling set point temperature, CO_2: stands for carbon dioxide concentration, R.H.: stands for relative humidity, A.H.: stands for absolute humidity and i: stands for step i of the data array, Y: stands for yes, N: stands for no).

ature and the indoor air quality function for indoor temperatures below this set point.

3) Shading function

The shading system, internal or external, is active (no intermediate steps) when the indoor temperature is over the shading temperature set point and the solar radiation affects the specific window of the zone (over 10° solar height and $\pm 60^0$ solar azimuth compared with the window).

Information of the building is configured on a web platform creating a project file in JavaScript Object Notation format. This project file together with the environmental parameters of every zone retrieved from an embedded computer every 10 min. Controlled actuators and motors (Fig. 1d) are connected with the gateway through radio communication signals (two in this research work). The gateway is connected with the embedded computer through a local area network (LAN). Algorithms run on a regular basis (user preferences) and perform evaluation and eventually actions to the motors. The application is connected to the embedded computer though a cloud service.

5. Results and discussion

5.1. Thermal comfort assessment, adaptive model

In order to evaluate the thermal indoor environment of all the monitored spaces of the house in room, floor and house levels, the upper and lower limit temperatures for both categories (1 and 2) and summer periods (2015 and 2016) were calculated, based on the running mean outdoor temperature (Eqs. (1) and (2)). For this case study, category 2 is employed (Table 5). A second stricter comfort definition is imposed also for the sake of the analysis (category 1). Fig. 4 presents the accumulated percentage of hours (from June to August) with thermal discomfort (overheating and undercooling deviation) for all the rooms of the upper floor (2015 and 2016) and living room and kitchen of ground floor (2016) for both 1 and 2 categories. Fig. 4c and Fig. 4d also present the thermal discomfort in house level (net volume average).

Four out of five rooms have faced overheating incidents in summer of 2015, assessed with the criteria of category 2 (Fig. 4a). The highest discomfort frequency and deviation (over 3%) were presented in the main bedroom and the daughter's room (Fig. 4a). These rooms have a tendency to overheat because of their southern orientation and the number of their openings (Fig. 1b). The undercooling incidents were negligible. The thermal discomfort of the upper floor, only overheating occurrences, was less than 2%. All the rooms managed to meet the requirement of the regulation, 5% [44,45].

Thermal comfort evaluation based on category 1 for 2015 (Fig. 4b) indicates that all the examined rooms have overheating and undercooling episodes with accumulated frequencies higher than 5%. All the spaces did not manage to achieve the suggested regulation requirement. Again the main bedroom and the daughter's room followed by the son's room present the highest overheating risk. The WC had more undercooling than overheating incidents. The WC has a north-east orientation and minimum occupancy and size. The discomfort frequency of the floor is close to 6%. In terms of thermal comfort, the floor belongs to category 2 for 2015. When undercooling is disregarded two out of five rooms do not manage to achieve requirements of category 1. Overheating risk for bedrooms is possible in all the calculated running mean outdoor temperatures (category 1) and over 16 °C for category 2 (not presented in this study). Undercooling incidents are critical mainly between 13.5 °C and 18.5 °C (category 1; all bedrooms). Overheating incidents are also possible in lower than 27 °C (Danish regulations) indoor temperatures for main bedroom (categories 1 and 2; [6]).

For summer of 2016, there were no overheating incidents in all rooms, apart from a single one in the living room (category 2; Fig. 4c). Undercooling is the only thermal discomfort issue for this period. The accumulated discomfort deviation is under 3% for all the monitored rooms of both floors. The most discomfort spaces were the son's room (north-west orientation) and the main bedroom, close to 2%. Floor thermal discomfort deviation was 0.3% (only undercooling occurrences). In general, the house in total managed not to deviate from the criteria of category 2 for the total investigated period.

Thermal comfort evaluation based on category 1 for 2016 (Fig. 4d) indicates that four out of seven examined rooms have

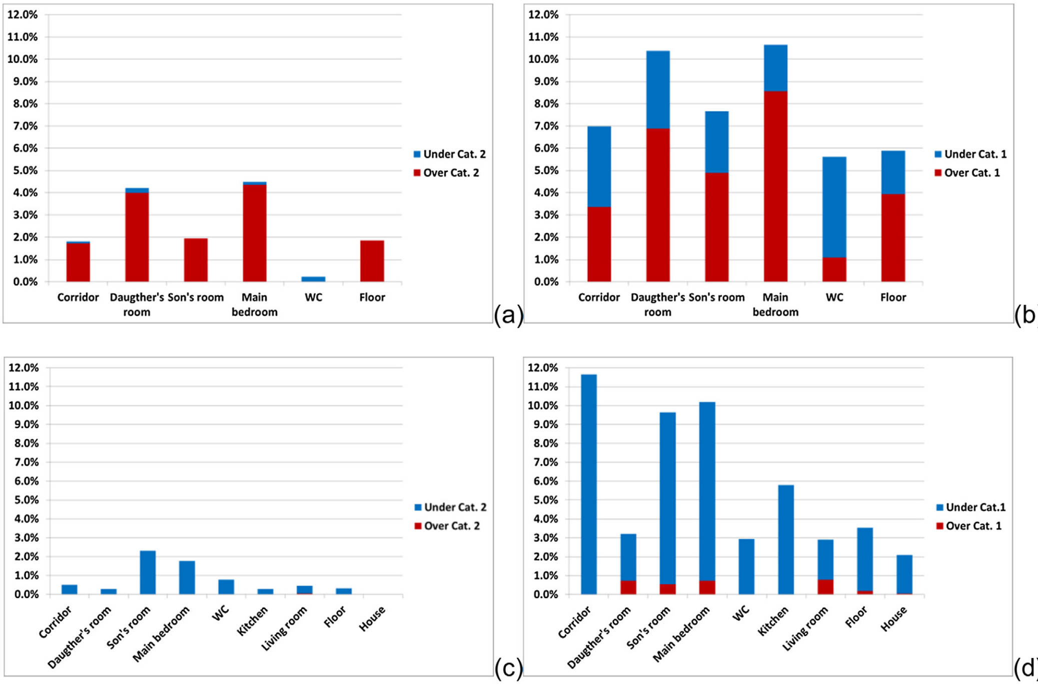

Fig. 4. Accumulated percentage (%) of discomfort (overheating and undercooling deviation) in room, floor and house level (c, d) of the case study for 2015 (a, b) and 2016 (c, d) and categories 1 (b, d) and 2 (a, c).

overheating and undercooling episodes. Rooms with only undercooling occurrences oriented to the north direction (Fig. 1b). In addition, four out of seven of the examined rooms have accumulated frequencies higher than 5% and do not meet the requirements of this category. The most discomfort spaces were the corridor (only undercooling) and the main bedroom (higher than 10%). The highest overheating risk is presented in the main bedroom and daughter's room for upper floor and in living room for the ground floor for category 1 (less than 1%). The corridor and son's room present higher discomfort values compared with 2015 (mainly undercooling instead of overheating). Floor and house in terms of thermal comfort belong to category 1 for 2016. For 2016 the hierarchy of the rooms is not identical for both categories in terms of discomfort, like it is for 2015. In terms of overheating risk, this hierarchy exists for all years and categories.

For the ground floor, living room meets the criteria of category 1 and kitchen the criteria of category 2 (only undercooling). There are no monitored data from the same period in 2015 for intercomparison. It is not safe to conclude that the cooling tendency of the upper floor with the installation of the window system in 2016 also cooled the rooms of the ground floor and especially the kitchen. The kitchen is a small room, which connected with the basement and the corridor of the ground floor with only one window to the north. The living room has similar discomfort episodes in comparison with the daughter's bedroom on the upper floor (same orientation). On one hand, the living room has more internal and solar gains compared to the daughter's room (Table 3). On the other hand, the living room is shaded more from the vegetation during the day and has significant thermal mass for heat storage. Façade window openings and shading activation for living room were not recorded for both investigated periods, but it is safe to assume that occupants ventilate the space less compared with the daughter's room

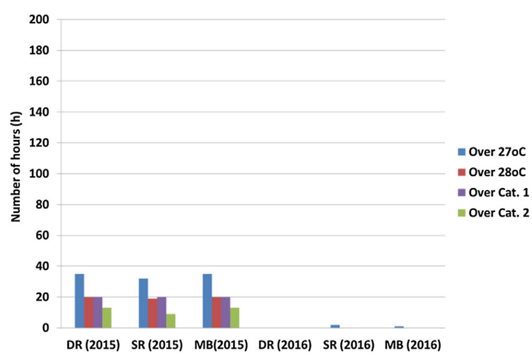

Fig. 5. Number of hours over static and dynamic thresholds (overheating; both categories) for the three bedrooms of the case study. (DR: stands for daughter's room, SR: stands for son's room and MB: stands for main bedroom) for 2015 and 2016 at night (23:00-07:00).

with the installed window system. Fig. 5 presents the overheating occurrences for the three bedrooms of the case study during night (23:00–07:00) for both examined years. The overheating incidents (both categories) during night for 2016 were zero. Fig. 6 shows that for bedrooms overheating risk exists in running mean outdoor temperatures over 18 °C (category 1) and indoor temperature over 26 °C (category 1). Undercooling incidents exist in all calculated running mean outdoor temperature values (both categories).

Table 7 presents the major user set points of the window system for all the examined rooms. The set points were constant for long periods and did not variate with the outdoor conditions. In

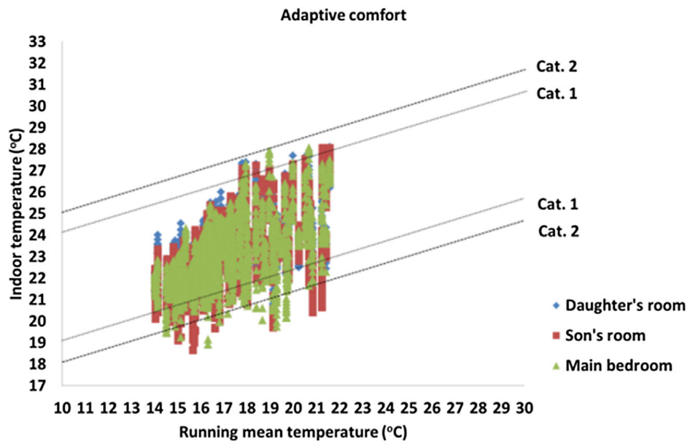

Fig. 6. Indoor temperature for all three bedrooms against running mean outdoor temperature for all the examined hours in 2016, including the category limits (1 and 2).

Table 7
User set points of the parameters of the window system for the different examined rooms.

	Corridor	Daughter's room	Son's room	Main bedroom	WC
Natural ventilation cooling temperature set point (°C)	24 (June: 22)	24	24 (June: 23)	24	24
Shading temperature set point (°C)	–	0∼+2	0∼+2	−3∼+2	out of use
Carbon dioxide set point (ppm)	1000	1000	1000	800	1000
Relative humidity set point (%)	60	60	60	60 (June: 50)	60–70

general, the users tried to solve local thermal (or visual) discomfort or air quality issues with overrides of the system. Time intervals of the control evaluation period were from 10 min to 1 h, but mainly 30 min.

The average monthly comfort temperatures were 24.6 °C for June, 24.7 °C for July and 24.2 °C for August (Eq. (1) and (2)). The average comfort temperature was higher than the natural ventilation cooling set point (24 °C maximum) for all the rooms of the upper floor. This behavior-action indicates that occupants of heating dominated temperate climates actually feel more comfortable in their bedrooms with indoor temperatures lower than those proposed by the regulations. The low night indoor room temperatures related mainly with their expectations and probably with their clothing. Many of the undercooling incidents for the corridor and the son's room were in June when the set points for ventilative cooling were low (22 °C and 23 °C respectively; Table 7). The main bedroom also had low set points (Table 7) for indoor air quality function (carbon dioxide concentration all period and relative humidity in June). Undercooling incidents were not a reported problem at the post occupancy evaluation survey from any member of the family. The use of the daily comfort temperature as a natural ventilation cooling set point, guarantees in a high percentage, an indoor space without discomfort (overheating and undercooling) risk.

The 3 functions of the window system were activated for the total of the examined rooms of the upper floor during the occupied and non-occupied hours (Section 4). Occupants of the main bedroom (June to August) and the daughter's room (middle of June to August) decided not to leave the system to open the windows during night. This decision was based on the fact that the beds are close to the roof windows, and the window opening was causing noise and disturbance to their sleep (Fig. 1d). Instead the users of these rooms were used to set a fixed window opening percentage (also 100%) and leave the windows open for the whole night or close them very early in the morning (Fig. 7a and b). The night and morning set points for the different occupancy states (morning and night occupancy states) varied significantly during the total examined period for all the rooms. Manual overrides of the window system during the night when the outdoor temperature were under 15 °C affected the indoor thermal environment of the rooms as expected, causing minor or major undercooling incidents (9 h over the benchmark of category 2 and 14 h over the benchmark of category 1; Fig. 7a). Minimum windows openings and activation only the one out of two roof windows are suggested for summer nights with low outdoor conditions.

In addition, the manual opening of the roof windows during the night occasionally affected the indoor air quality of the room for the next day (humid environment). For parallel use of cooling and indoor air quality functions, the windows follow the cooling function (in priority) for indoor temperatures over the natural ventilation cooling set point temperature and the indoor air quality function for indoor temperatures below this set point. As a result, window opening based on the indoor air quality function of the window system caused exacerbation or continuation of the undercooling risk (Fig. 7a). A second time interval parameter has to be integrated to the window system (indoor air quality function) in the future. The applicability range (difference between indoor and outdoor temperature) has to be reconsidered also in the future (Section 4). In general, benchmarks and categories proposed for indoor relative humidity do not apply to residential buildings [45]. The relative humidity control of the indoor air quality function of the window system has to be reconsidered in the future to cover only severe violations on specific rooms (Section 5.2).

In general, the window system effectiveness, in terms of ventilative cooling, is discernible and discreet (Fig. 7b). The day and night ventilative cooling diminished the overheating risk and prevented extreme indoor temperatures (typically 2–3 °C higher than the outdoor temperature). The activation of the external shading system (manual override) during daytime would diminish the overheating risk of this particular day to the minimum (Fig. 7b). The manual

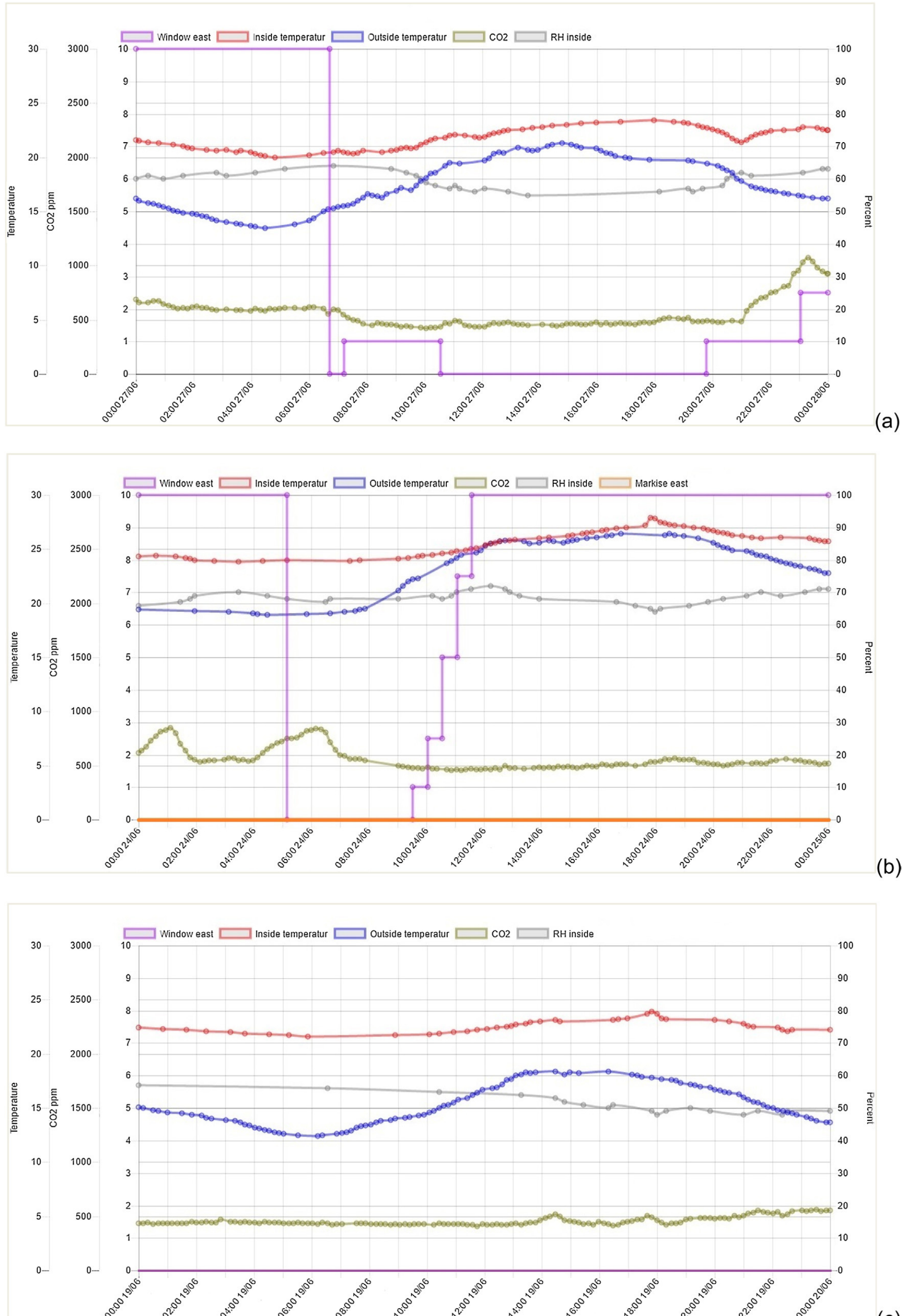

Fig. 7. Indoor environment (temperature (°C), relative humidity (%) and carbon dioxide (ppm)) of different rooms of the upper floor (a: main bedroom, b and c: daughter's room) and window and shading position (%).

override of the shading systems was a common practice for the occupants of the case study (visual contact with the outdoor environment). Typically the shading systems were used in bedrooms to prevent the morning sun to disturb the sleeping process. The energy savings from the deactivation of the mechanical ventilation add extra value to the effectiveness of the system. The system is used only when it is necessary with minimum energy consumption for the motors and actuators (Fig. 7c).

The use of the system is possible during the transition months and heating season. Typically, during these periods the difference between indoor and outdoor temperature is larger than 10 °C. The use of the window system is possible only through manual control. An economic evaluation of the yearly performance of the window system for the verification of the viability compared with the mechanical ventilation system is suggested also for future work.

5.2. Overheating assessment, fixed thresholds

All the rooms, apart from WC, present on average lower temperatures in 2016 compared with 2015 (not presented in this study). Maximum indoor temperatures are also lower for 2016 for all rooms. The maximum indoor temperature for 2015 is in the main bedroom (31.6 °C) and for 2016 in all 3 bedrooms (28.1 °C). The minimum indoor temperature for 2015 is in the corridor (19 °C) and for 2016 in the son's room for upper floor and living room for ground floor (18.7 °C and 18.5 °C respectively). The WC, son's room and main bedroom have lower minimum indoor temperature in 2016 compared with 2015. The range of indoor temperatures in floor level is shorter for 2016. This implies that the indoor temperature does not fluctuate considerably in short periods.

Danish building regulation criteria were used to analyze the data in order to assess the risk of overheating in critical rooms (bedrooms) and in floor and house level (possible only in 2016). Cooling period in Denmark also includes the transition months May and September. The exceeded hours over the thresholds assessing the whole cooling period are possible to be slightly higher for 2015.

Thresholds values were exceeded for more than 100 and 25 h respectively for all three bedrooms in 2015 (Fig. 8a). Corridor has exactly 100 h over 27 °C in 2015. WC meets the requirements for the first benchmark in this season. The second requirement (maximum 25 h above 28 °C) was not fulfilled in any room of upper floor for 2015. For 2016 all rooms of upper and ground floor fulfill both benchmarks and meet the criteria of the regulation (Fig. 8b).

The highest overheating risk is presented on the main bedroom for both years (27 °C). The second highest on upper floor is presented in the daughter's room (27 °C). The living room presents also overheating risk (2016). For 2016, the corridor and kitchen show no overheating incidents (27 °C). The incidents over the second benchmark for 2016 are negligible. The hierarchy of the bedrooms in terms of overheating is similar for both benchmarks in 2015 and 2016. The overheating incidents (both thresholds) during night (23:00-07:00) for 2016 were negligible (Fig. 5).

The upper floor does not manage to meet both criteria for 2015: 106 and 65 h respectively. On the other hand overheating incidents in floor and house level in 2016 was 20 and 17 h respectively (meet the requirement). No hours over 28 °C were calculated in floor and house level respectively.

Static and dynamic assessment methods cannot be compared directly because they evaluate different indoor thermal conditions, thermal discomfort and overheating. The static index of the local regulation fails to identify and quantify the undecooling issue that arises in many rooms during the cooling period. The discomfort from undercooling incidents and low temperatures in bedrooms during the night period of hot summer periods has to be investigated in the future. Both methods highlight the rooms with the major overheating risk (and hierarchy).

5.3. Indoor air quality assessment

As far as the carbon dioxide concentrations, all the bedrooms fail to meet the requirements of category 2 apart from the main bedroom during the summer of 2015 (Fig. 9). The daughter's room for 2016 has lower deviation from category 2 (close to 10%) compared with 2015 and slightly better indoor environment (set point 1000 ppm). The daughter's room in 2015 reveals the poorest results among all the examined spaces and years. This room meets category 2 requirements only the 83.1% of the examined time. The opposite situation was assessed for the son's room (set point 1000 ppm). Category distributions for the main bedroom are identical for both years (set point 800 ppm). In 2015, 95.3% of the hours meet the requirements of category 2 and 92.2% for 2016.

All rooms of the upper floor for both years, in terms of relative humidity, meet the requirements of category 3 (Table 8). In addition, all rooms fulfill the requirements of SBI 224 and the percentage of hours with relative humidity over 75% is less than 1% [47]. The percentage of hours (not presented in this study) over this benchmark for WC is 1% for 2015 (maximum value 82%) and 0.8% for 2016 (maximum value of 78%; Table 8).

The air quality of the indoor environment for both cooling seasons is similar with small deviations. Window system performance (integrated only in roof windows), in terms of indoor air quality, is straight comparable to the effectiveness of the combined use of the mechanical ventilation system and the manual use of the openings.

6. Conclusions

Major and deep energy renovations on residential and other buildings are expected in Denmark and in Europe over the next several years. The ability of the strict measures and targets of the new standards, initiatives and regulations to provide high quality indoor environment during the cooling periods is one of the main concerns.

The thermal and air quality assessment of a deep energy renovated typical single-family house in Denmark during mild summer conditions verifies the fact that active and passive ventilation and shading systems, if manually controlled, cannot guarantee and assure high quality indoor environment without potential violations. As a result, critical rooms with high internal and solar load or other restrictions and limitations do not manage to meet the requirements of the existing regulations and standards.

In contrast, the use of an automated window system with integrated heuristic straightforward passive cooling control strategies may significantly decreases the thermal discomfort and overheating risk in room and house levels without any significant compromise of the indoor air quality. Window system effectiveness in terms of thermal quality and overheating risk, assessed by dynamic and static methods, is discernible. The total energy savings from the deactivation of the energy consuming mechanical ventilation system add extra value to the effectiveness of the system.

Static criteria and methods suggested by local regulations fail to identify all the possible discomfort issues, which arise during cooling periods. These issues are mainly overheating incidents on lower indoor temperatures than those suggested by the regulations and undecooling occurrences. The effect of the undercooling discomfort incidents (deliberate choice of the users) during hot summer periods on rooms with sleeping activity has to be investigated in the future through post-occupancy surveys and questionnaires. Inves-

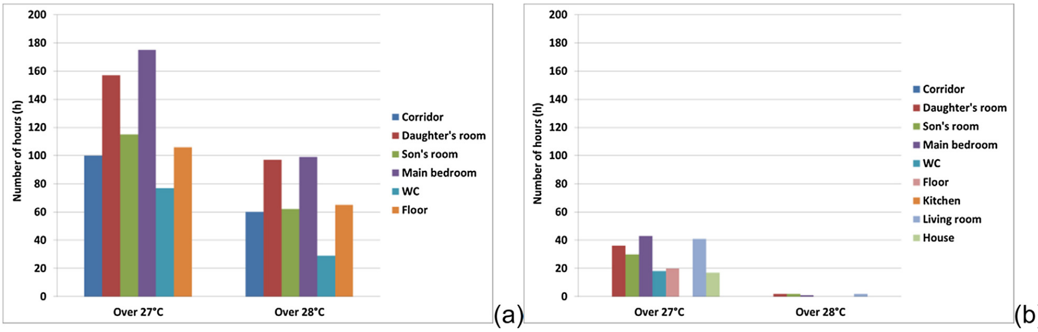

Fig. 8. Number of hours over 27 °C and 28 °C for all monitored rooms for 2015 (a) and 2016 (b).

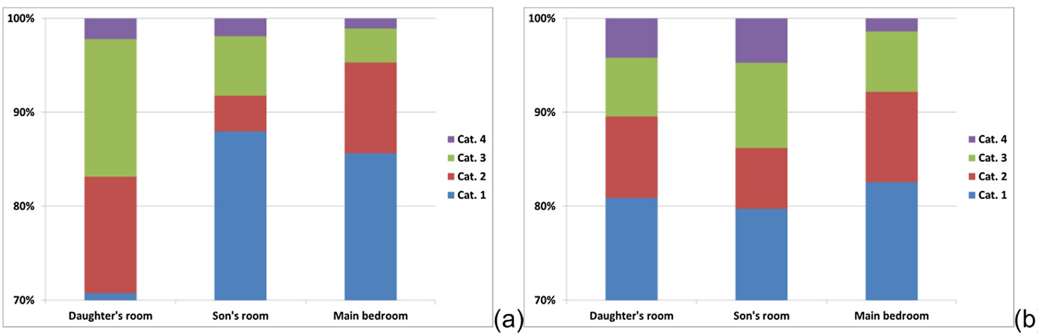

Fig. 9. Indoor air quality (dioxide carbon concentration) assessment for the three bedrooms of upper floor for 2015 (a) and 2016 (b).

Table 8
Percentage of hours (%) with relative humidity over 70% for different rooms and examined periods.

	Corridor	Daughter's room	Son's room	Main bedroom	WC
2015	0.2%	0.0%	0.0%	0.4%	4.2% (max.: 82%)
2016	1.4%	1.7%	2.0%	1.8%	4.7% (max.: 77.5%)

tigation of the user behavior (set points and override reasons) on windows systems through log books suggested also for future work.

In the current study the window system controls only a small part of the available passive systems of the house (roof windows and shadings). The description of the structure and the architecture of the window system can be used as a baseline for further development of window systems for residential cases in temperate climates or more complicated layouts and types of buildings. The suggestions for improvements and the limitations of the system have to be included in this effort. The user adopted environmental parameters and set points of this monitoring campaign can be used also as reference targets or supporting material for already installed window systems in temperate climates.

Acknowledgements

The authors would like to express their thanks to the owners of the house. Their cooperation during the period of the monitoring campaign was more than valuable. The authors are presently contributing to the ongoing work for investigating and maturing ventilative cooling as an attractive and energy-efficient solution to avoid overheating of both new and renovated buildings within the IEA EBC Annex 62: Ventilative Cooling. The research was developed within the framework of the project "Ventilative cooling in energy renovated residences" of Aalborg University, Denmark, and was supported by EUDP (Energy Development and Demonstration Programme) and VELUX A/S, DOVISTA A/S and VISILITY ApS.

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Appendix IV

Article 4

Psomas T, Fiorentini M, Kokogiannakis G, Heiselberg P. Ventilative cooling through automated window control systems to address thermal discomfort risk during the summer period: Framework, simulation and parametric analysis. Energy and Buildings Journal (submitted 7.5.2017). Reprinted by permission of the Editor of the Journal.

Ventilative cooling through automated window control systems to address thermal discomfort risk during the summer period: Framework, simulation and parametric analysis

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Keywords

Residential building, simulation coupling, adaptive thermal comfort, domestic automation, building energy performance

Abbreviations

BCVTB	Building controls virtual test bed software
BPS	Building performance simulation (tool)
ESRU	Energy Systems Research Unit of the University of Strathclyde
EU-28	European Union (28 members)
HVAC	Heating ventilation and air conditioning systems
LBNL	Lawrence Berkeley National Laboratory
POR	Percentage outside the range index
RBC	Rule based control

Abstract

Automated window control systems with integrated ventilative cooling strategies may significantly diminish the thermal discomfort and overheating risk of dwellings during cooling periods in temperate climates. One of the challenges with demonstrating the benefits of the systems is the lack of building performance simulation (BPS) tools which may represent precisely how actual ventilative cooling algorithms are applied.

The study supported herein aims to present a framework of how to simulate an advanced ventilative cooling algorithm of an automated window control system on coupled BPS environments (ESP-r and BCVTB tools). Parametric analysis has been conducted to verify specific operational functions (control approaches) of the system. The analysis uses a representative single-family renovated house in Denmark.

Parametric analysis was found that the performance of the developed ventilative cooling strategy for these climatic conditions was not affected by the number of opening steps (3 or 5) for low and medium natural indoor ventilation cooling set points (22-24°C). For all the examined spaces, the static trigger set points perform better than the dynamic for all the evaluating metrics and criteria that were included in this study. Under the proposed framework, the simulation of any other developed ventilative cooling concept or system is possible.

1. Introduction

In Europe, the building sector in 2010 was the largest end-use sector, consuming approximately 40% of the total final energy requirements [1,2]. In EU-28 the majority of the stock is residential buildings and more specifically single-family houses [3]. In the USA, residential buildings consume approximately 23% of the total energy end use in all sectors and the half of that is for space heating and cooling demand [4]. The global cooling use of the residential buildings for 2010 represents approximately 4.4% of the total thermal needs [5]. This percentage is expected to be increased up to 35% in 2050 and 61% in 2100 mainly because of the climate change (global warming, heat island effects and heat waves), the increased living standards, the higher comfort requirements, the penetration and boosting of the air-conditioning industry and the globalization of modern west-style architecture [2,6]. The total thermal demand also will be expected to increase up to 67% in 2050 and 166% in 2100 from 2010 levels [5]. In addition, previous research has documented incidents of extensive overheating when mechanical cooling is not used in new nearly zero energy and in deep renovated residential buildings in the temperate climates of the central and western Europe [7-10]. A number of post-occupancy surveys have also shown elevated indoor temperatures even in heating dominated Northern European temperate climates [11,12]. The strict requirements for high energy efficiency in building regulations, guidelines and standards for new or existing buildings with major renovations in temperate climates are oriented mainly to the heating season and they often underestimate the potential issues that could arise with regards to indoor air quality and thermal comfort during the warmer months (simplified monthly methods, in house not in room level; [13]). The building occupants of these climates do not have the knowledge of how to efficiently diminish their thermal discomfort indoors and their behavior, preferences and attitude might instead increase it [14]. In general, overheating risk greatly affects health, productivity, morale, satisfaction and well-being of inhabitants [15].

Experimental research, in real buildings and test cells, and theoretical research have shown that attractive passive cooling methods, tools and technologies and more specifically ventilative cooling provide excellent indoor thermal conditions and air quality with minimum energy use [2,16]. The effectiveness of ventilative cooling strategies depends on the availability of a proper natural heat sink (external air mass) with satisfactory temperature gradient and the efficient thermal coupling between the sink and the thermal mass [17,18]. In most cases, night ventilation strategies could considerably decrease the peak temperature of the next day for "free-running" buildings and the cooling load for air-conditioned spaces [2,18]. Extensive research has revealed that occupants in naturally ventilated residential buildings have larger comfort acceptability and suffer less from "sick-building" symptoms compared to those in conditioned spaces [15,19]. Operable natural ventilation systems significantly reduce the energy needed for cooling and ventilation and the overheating risk for non-conditioned spaces [20,21].

Window opening behavior is related with psychological and social factors, education, lifestyle, building characteristics, position of the opening in relation to the location of the occupants in the building and indoor and outdoor conditions [22-26]. Most of the developed models on window opening patterns refer to office buildings and moderate climates. Occupants control on window opening or simple venting schedules lead to thermal discomfort risk and unnecessary energy waste, undermining the energy savings that natural ventilation could offer [27,28]. Various researchers have examined the impact on building energy consumption that the window use has in different temperate climates [29-32]. Fabi et al. have described a methodology for the application of window opening occupant behavior for residential buildings in building performance simulation (BPS) tools [33].

Advanced ventilation technologies with smart control algorithms may considerably reduce the energy share of the cooling demand [34]. A continuously higher penetration of automation control systems is expected in the coming years not only in large scale buildings but also in individual houses, transforming them into intelligent smart houses [35,36]. Building automation systems monitor, control and optimize the indoor environment, the energy use and the cost savings. These systems are able to communicate with each other, return control to the user and give him feedback [37]. Window opening systems that match the needs of occupants and the building characteristics have high saving potential for ventilation and cooling [28,38]. However, the application of automated control systems integrated on window configurations (roof or façade), hereafter called “window systems”, in houses is still limited.

Karjalainen has concluded (2013) that the system characteristics which improve the level of trust between the user and the domestic system are the predictability, the transparency, the individual control opportunities, the simplicity, the usability and the suitability for daily life [39]. Window systems with rule-based-control (RBC; heuristic control) are the conventional approach and the industry standard [40]. The RBC is based on “IF (condition)-THEN (action)” rules and introduce the expert knowledge into the control loop [41]. Schulze et al. (2013) and Martin et al. (1996) concluded that complex algorithms in many buildings do not perform better than simple ones and setting parameters proved more important than the control strategy itself [42,43]. Advanced window systems are complex (especially for large buildings), need sufficient computing power (huge data collection), are model and assumptions dependent (fidelity), are expensive for medium size buildings, and are not user friendly for operators [44,45].

Literature review concludes that there were no well documented, mature and validated BPS tools which could represent the state-of-the-art ventilation and passive cooling control strategies [17,42]. Controls improve performance considerably and, as a result, the control representation in BPS tools needs to mirror precisely how actual algorithms are developed and applied [46]. Idealized controls that exist in many tools cannot substitute these algorithms effectively [46]. The study supported herein aims to present a methodology and a framework of how to simulate a developed ventilative cooling algorithm of a window system on coupled BPS environments. The window system is oriented to address mainly overheating risk during peak summer periods. The ventilative cooling algorithm is presented analytically in Section 2.1. In addition, parametric analysis has been conducted to document and verify specific operational functions of the window system. These operational functions are related mainly with the number of steps of window opening (step-approach) and the nature (dynamic or static) of the indoor natural ventilation cooling set point (Section 2.1). The window system at its current form uses a 5-steps approach and static indoor natural ventilation cooling set points (Fig. 2).

This analysis used a 1930s single-family deep renovated house close to Copenhagen, Denmark and the BPS software ESP-r. For the simulation and realistic representation of the control algorithm, the ESP-r software is coupled with Building Controls Virtual Test Bed (BCVTB) tool. The model was calibrated to represent, as close as possible, the real indoor environment of the dwelling (analytical monitoring campaign during the summer of 2016). The calibration process is highlighted as the initial part of the proposed framework and workflow for the verification and documentation of the ventilative cooling performance of the developed window systems or any other window system. In addition, the conclusions of the parametrical analysis, as far as the examined operational functions of the window system, will be directly applicable for the further development of the system. Both static and dynamic thermal discomfort and overheating risk metrics are used to perform comfort assessment for the whole period of the analysis.

2. Methodology

2.1 Software description and coupling

For the realistic representation and simulation of the function of the new developed window system (effect to the dynamic thermal environment), a custom virtual environment has been created with the use of two well-documented tools, ESP-r and BCVTB (Fig. 1). A limited number of building simulation software has currently the capability to simulate the effects of a relatively complex algorithm for natural ventilation and ventilative cooling, and for this reason a time step coupling with an external emulator for controllers has been considered. ESP-r and BCVTB could offer the possibility to achieve this goal, if their standard capabilities are extended to include external controller of flow network components [47,48]. The connection between ESP-r and BCVTB was previously developed and presented by Hoes et al. [49]. In this research work the HVAC heating and cooling load was managed by a controller, developed in Matlab, via BCVTB. In a previous study, focused on an evaluation methodology and implementation for natural ventilation control strategies, Fiorentini et al. (2016) integrated the BCVTB communication functions in the ESP-r code to achieve time step control of the opening components [50].

ESP-r is a state-of-the-art open-source BPS software initially developed by the Energy Systems Research Unit at the University of Strathclyde (ESRU; [47,51]). ESP-r is based on the finite volume method and it has been under constant development and validation for more than three decades [52,53]. Dynamic thermal building response and multi-zone airflow phenomena are accurately represented in ESP-r [54]. A further advantage is that the ESP-r code is transparent to developers and may easily be expanded, modified and recompiled. The integrated airflow network allows air paths to be described in detail (response to outdoor conditions and control; [53]). Generic pressure and flow resistances coefficient are integrated in the tool and are described in [54]. Typical window controllers use indoor air temperature (virtual sensor) to trigger opening (actuator) at a certain percentage and/or proportional control with hysteresis above a benchmark [55]. The open nature of the code allows the development and integration of self-developed algorithms and link with other tools [56].

BCVTB (version 1.5.0) is an open-source (Java based) and free available software platform developed by Lawrence Berkeley National Laboratory (LBNL) for coupling different simulation programs (middleware) and information exchange (real-time data exchanger; [48]). BCVTB is an extension of Ptolemy II, a program developed for heterogeneous simulations [57]. Relatively complex controls and algorithms may also be implemented directly in its interface.

The input data may be categorized into two types: parameters and variables. The parameters refer to the data that remains constant during the building simulation process and variables refer to the data that might change during the simulation. The coupling of the two software allows the exchange of an array of numerical values between the ESP-r model and the BCVTB controller at the beginning of each time step (measured states, $x(k)$, and measured disturbances $u_d(k)$ at each time step k; Fig. 1). The measured states array includes the zones indoor temperatures. The measured disturbance is the outdoor temperature (current time is also exchanged). The arrays of measured and disturbances states replicate the real-time sensor measurements that act as inputs in the window system. The control loop closes with the BCVTB controller, which could emulate any control logic and return an array of opening percentages $u_c(k)$ for all the operable windows in each zone.

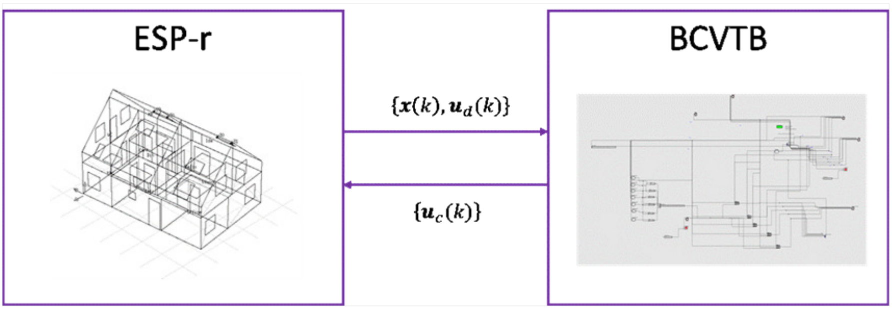


Fig. 1 Graphical representation of the communication architecture (measured state-disturbance and window opening) of the coupled tools (ESP-r and BCVTB).

The ventilative cooling algorithm of the window system is summarized below (Fig. 2). The operable windows in each zone are activated by independent controllers. Windows of every examined zone open incrementally with 5 discreet steps when the ambient air temperature is lower than the indoor operative zone temperature and when the indoor operative temperature is higher than the indoor natural ventilation cooling set point. Indoor ventilative cooling set point is a static operative temperature set point at its current form. The 5 discrete steps for window opening were 10%/25%/50%/75%/100% of the motor actuator, as described in detail in [28]. After each control time step, which in this study was considered to be equal to 30 minutes, if the indoor operative temperature is higher than the previous time step, the opening percentage increases to the next incremental step, otherwise the opening remains unchanged. The algorithm was applied to all the roof windows of the zones of the upper floor of the case study presented in Section 2.2.

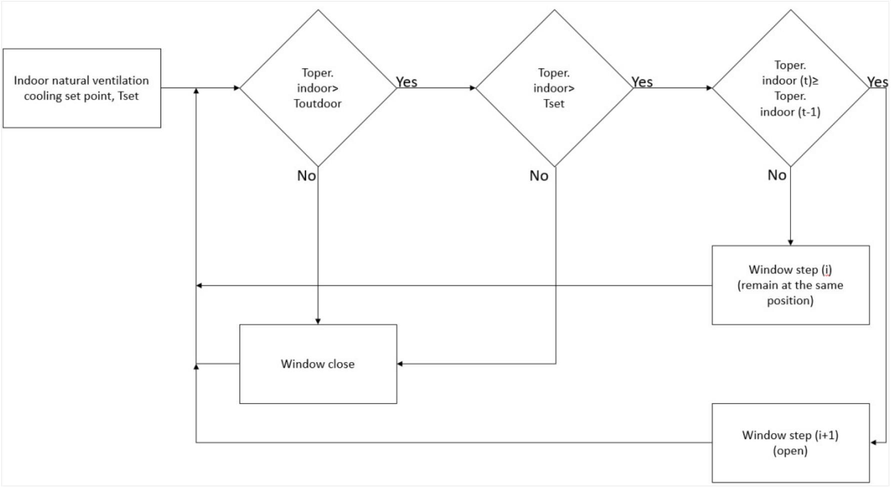


Fig. 2 Ventilative cooling algorithm integrated to window system. (T: stands for operative temperature (zone), T_{set}: stands for indoor natural ventilation cooling set point (dynamic or static), i: stands for window opening step (maximum 3 or 5-steps) and t: stands for time interval (30 minutes)).

2.2 Case Study

This section presents the technical and thermal characteristics and details of the dwelling used to demonstrate the method for enabling the windows opening algorithm to be modelled when the ESP-r building simulation tool is coupled with the BCVTB controls emulator platform. The algorithm was implemented in a real house, which was audited and monitored to collect data for calibrating the building model. The simulated house is a typical 1930s yellow-brick single-family house located at a suburban area close to Copenhagen, Denmark. The gross area and the surface-to-net-volume ratio are 172.4 m^2 and 0.47 m^{-1} respectively. The house is a two-storey detached building with a pitched roof and a basement. It is surrounded by vegetation at the southern orientation. The house is occupied by a four-member working family with two children and has been significantly renovated over the last years. The deep renovation covers the increase of the efficiency of the building envelope and the installation of nine high-performance pivot roof windows with electrically driven motors and actuators. Both floors have brick walls. For the ground floor, the insulation is inside the external wall (compressed), and for the upper floor, the insulation is internal (with gypsum boards covering). The roof windows with the integrated shading systems were installed at the corridor, the W.C. and the three bedrooms (Fig. 3). Side-hung windows are double-glazed from the middle 1990s (not renovated). The doors of the house are wooden and the internal space is light-white colored. The service rooms are at the ground floor and through stairs there is a connection with the basement. The balcony on the south part of the upper floor functions as an overhang for the facade windows of the ground floor. Table 1 presents the thermal characteristics (U-value) of the case study envelope elements (both floors). Table 2 presents the window-to-net floor area ratio for all the examined rooms of the upper floor of the house.

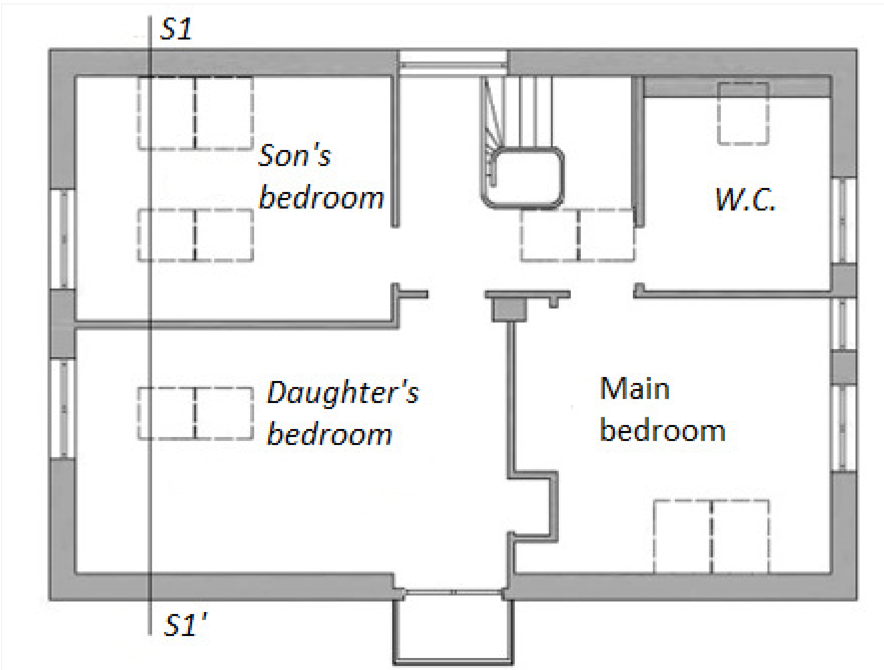


Fig. 3. Architecture floor plan of the simulated upper floor (three bedrooms, W.C. stairs and corridor) of the examined case study (roof and façade windows are indicated).

The case study has been simulated according to its design specifications in ESP-r (Table 1), with an airflow network that accounts for internal air movement between spaces, ventilation through windows and infiltration. The internal thermal mass values and the thermal characteristics of the non-renovated materials (e.g. old Danish bricks) were extracted from International Standards [58]. The case study has been simulated as a free running building without mechanical ventilation and active systems (heating and cooling) for the three examined summer months (June, July and August) of 2016 (Fig. 4). The only simulated active system was the controllable window system. The façade windows of both floors (used only the roof windows) remained closed for the total examined period and the active shading system was not used during the simulation. Tables 3 and 4 present information about the occupancy and the internal heat gain profiles (appliances and lighting) respectively for two day types (weekday, weekends). The occupancy profile was derived from an interview-survey with the family. Default values for the radiant and convective fraction of the internal gains has been used [53]. Homogeneous air properties and full air-mixing were assumed as well [54]. The initialization (warm-up) period for the analyses of this research work was 15 days.

Table 1

U-value (W/m^{2}K) of the simulated envelope elements of the case study (both floors).

Floor	External wall	Ceiling-roof	Internal partition	Floor	Façade windows	Roof windows
Ground	0.37	0.21	2.48	0.19	2.70	-
Upper	0.16	0.11	0.32	0.21	2.70	1.10

Table 2

Window-to-net floor area ratio (%) for the different examined rooms of the upper floor.

Corridor (North)	W.C. (North-East)	Main bedroom (South-East)	Daughter’s room (South-West)	Son’s room (North-West)
31	28	30	32	36

Table 3

Developed occupancy daily profile (weekdays and weekend; office, dining room and living room: 108 Watts, kitchen: 126 Watts and bedroom: 90 Watts).

Hour of	Weekdays			Weekend		
the day	Parent 1	Parent 2	Children	Parent 1	Parent 2	Children
1	Bedroom	Bedroom	Bedroom	Bedroom	Bedroom	Bedroom
2	Bedroom	Bedroom	Bedroom	Bedroom	Bedroom	Bedroom
3	Bedroom	Bedroom	Bedroom	Bedroom	Bedroom	Bedroom
4	Bedroom	Bedroom	Bedroom	Bedroom	Bedroom	Bedroom
5	Bedroom	Bedroom	Bedroom	Bedroom	Bedroom	Bedroom
6	Bedroom	Bedroom	Bedroom	Bedroom	Bedroom	Bedroom
7	Bedroom	Bedroom	Bedroom	Bedroom	Bedroom	Bedroom
8	Dining room	Dining room	Dining room	Dining room	Dining room	Dining room
9	-	-	-	Office room	Living room	Bedroom
10	-	-	-	Office room	Living room	Bedroom
11	-	-	-	Office room	Living room	Bedroom
12	-	-	-	Office room	Living room	Bedroom
13	-	-	-	Office room	Living room	Bedroom
14	-	-	-	Office room	Living room	Bedroom
15	-	-	-	Office room	Living room	Bedroom
16	-	-	-	Office room	Living room	Bedroom

17	Living room	Kitchen	Living room	Living room	Kitchen	Bedroom
18	Dining room	Dining room	Dining room	Dining room	Dining room	Dining room
19	Living room	Living room	Bedroom	Living room	Living room	Bedroom
20	Office room	Living room	Bedroom	Living room	Living room	Bedroom
21	Office room	Living room	Bedroom	Living room	Living room	Bedroom
22	Office room	Living room	Bedroom	Living room	Living room	Bedroom
23	Office room	Living room	Bedroom	Living room	Living room	Bedroom
24	Bedroom	Bedroom	Bedroom	Bedroom	Bedroom	Bedroom

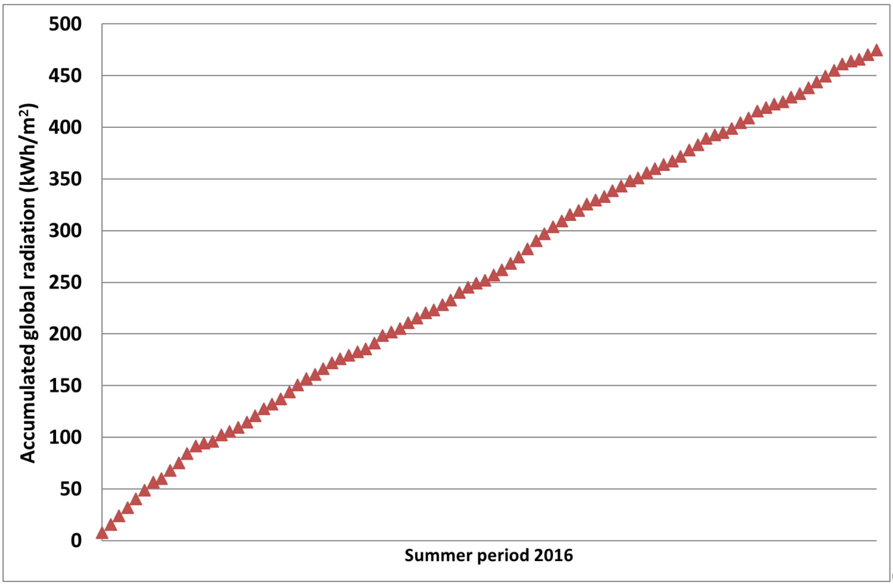
Table 4

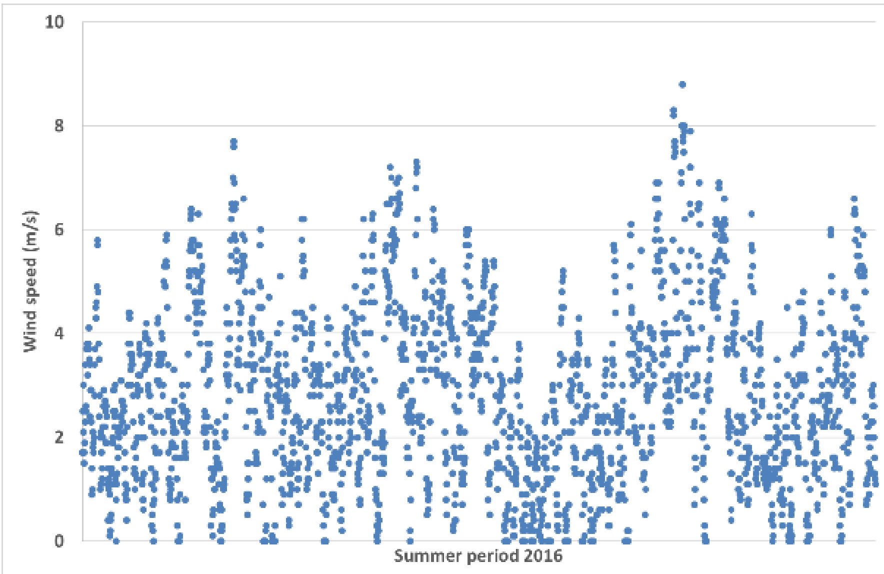
Internal heat gains daily profile [59].

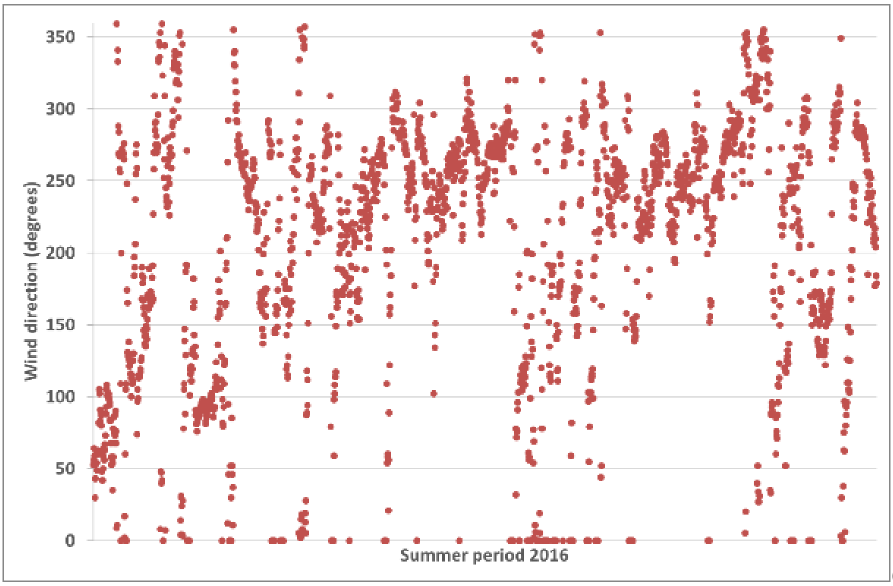
Hour of the day	Appliances (x2.4 W/m^2)	Lighting (x8.0 W/m^2)
1	0.5	0.0
2	0.5	0.0
3	0.5	0.0
4	0.5	0.0
5	0.5	0.0
6	0.5	0.0
7	0.5	0.15
8	0.7	0.15
9	0.7	0.15
10	0.5	0.15
11	0.5	0.05

12	0.6	0.05
13	0.6	0.05
14	0.6	0.05
15	0.6	0.05
16	0.5	0.05
17	0.5	0.2
18	0.7	0.2
19	0.7	0.2
20	0.8	0.2
21	0.8	0.2
22	0.8	0.2
23	0.6	0.15
24	0.6	0.15

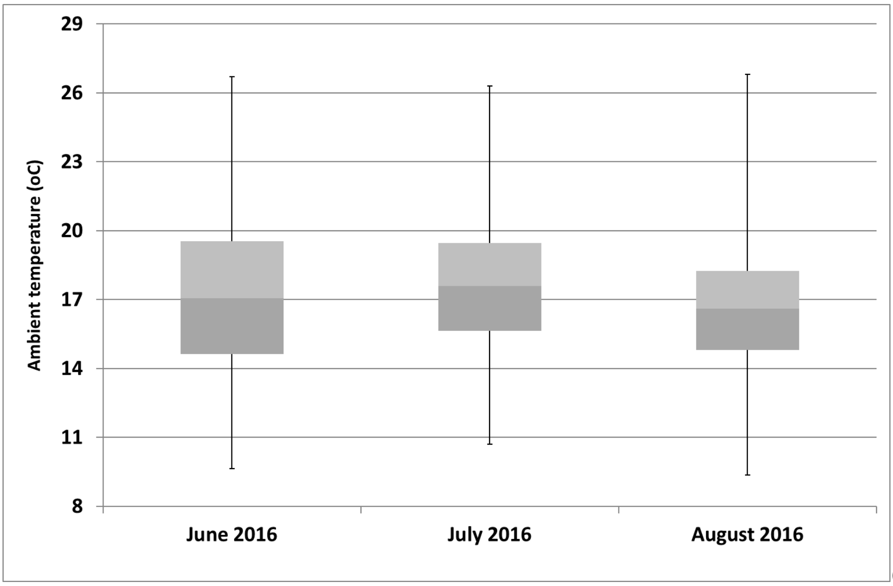
Real weather data of global radiation, wind speed intensity and direction were taken from the closest meteorological station of the Danish Meteorological Institute, Sjælsmark, 3.7 km away from the building (Fig. 4a, b and c). The outdoor ambient temperature was measured *in-situ*, with a calibrated sensor that was totally protected from solar radiation by being encapsulated in silver plastic box. Weather conditions during the examined summer period (June to August, 2016) were typical for the area and period [28]. The hottest month, in terms of average temperatures, was July followed by June. August had the highest and the lowest temperature during the 3-month examined period. The wind intensity ranged mainly from 1.4 to 3.9 m/s (North-West and South-West orientations).


Accumulated global radiation (kWh/m²)
500
450
400
350
300
250
200
150
100
50
0
Summer period 2016
(a)


Wind speed (m/s)
10
8
6
4
2
0
Summer period 2016
(b)



(c)



(d)

Fig. 4. a) Accumulated horizontal global solar radiation (kWh/m^2), b) wind speed (m/s), c) wind direction (degrees) and d) ambient air temperature (^{o}C) of the location of the dwelling during the summer period (June to August) of 2016.

2.3 Performance indicators

For more than seven decades, over 160 different climatic stress indices have been developed and have been reported in the literature [60], of which over seventy indices (70) were for overheating risk assessments [61]. The majority of these indices are related either on comfort models and acceptability ranges or health evidences [62]. For the past years, a new discomfort index has been developed describing in one number the long-term discomfort of indoor spaces for different building types [59,61]. The index was embedded in the derived dynamic adaptive models and tools, which are used widely for naturally ventilated and non-mechanically cooled residential buildings, because it was found that they reflect the user's perceptions and experiences for thermal comfort in these types of buildings [59]. In houses, there are different ways of thermal adaptation through clothing and activity modification and environmental control on building systems (windows, blinds, fans and others; [63,64]).

This research work uses two widely applied metrics and four criteria for the assessment of the discomfort conditions during the examined period. The first metric is the "percentage outside the range-POR", which accumulates the hours over the examined-simulated period (percentage of total hours) during which the indoor zone operative temperature is higher or lower than the boundaries-limits of the dynamic adaptive comfort theory (Eqs. (1) and (2); [59]). Table 5 presents the Categories for the values to be used when calculating the upper and lower limits of Eq. 1. Category I refers to buildings occupied by fragile or elderly people, with high level of expectations in terms of indoor conditions and thermal comfort [59]. Category II represents a normal level of expectation (new buildings or renovations). Category III represents an acceptable-moderate level (existing buildings). Category IV is acceptable only during a limited part of the year. The first part (without category range) of Eq. 1 is the comfort temperature.

$$T_{i,op.max/min} = 0.33 * T_{rm} + 18.8 \pm \text{Category range limit (Equation 1)}$$

$$T_{rm} = (T_{ed-1} + 0,8 * T_{ed-2} + 0,6 * T_{ed-3} + 0,5 * T_{ed-4} + 0,4 * T_{ed-5} + 0,3 * T_{ed-6} + 0,2 * T_{ed-7})/3.8 \text{ (Equation 2)}$$

$T_{i,op.max/min}$: limit value of indoor operative temperature (°C)

T_{rm}: running mean outdoor temperature (°C).

T_{ed-i}: daily mean ambient temperature for the previous i day (°C)

Table 5

Limit value of indoor operative temperature for the different Categories [59].

	Category I	Category II	Category III*
Upper limit	+2	+3	+4
Lower limit	-3	-4	-5

*Category IV includes the indoor operative temperatures above or below the other Categories.

The second metric is the temperature excess which is defined as the cumulative number of hours with indoor operative temperatures over static thresholds. Literature extensively uses this method because it is simple and easily understandable and communicable by non-technical users [61]. Danish regulations forward fixed thresholds and hours of exceedance for critical rooms (100 hours over 27°C and 25 hours over 28°C; [13]). This research work employs the suggested static thresholds of the Danish regulations for the assessment of the overheating risk (percentage of time, %). The compliance with the regulations for both metrics and criteria is outside of the interest of this research work [13, 59].

3. Results and discussion

3.1 Model calibration

The first step prior to simulating the performance of the ventilative cooling method with the different control options was to undertake a model calibration process. The calibration process is highlighted as the initial part of the proposed framework for the verification of the ventilative cooling performance of the developed window systems or any other window system. In addition, the conclusions of the parametrical analysis, as far as the examined operational functions of the window system, will be directly applicable for the further improvement of the system.

The model was calibrated using house monitoring data acquired between 13th-18th June. The indoor sensors (similar with the outdoor sensors) were calibrated and installed in locations, where they were not exposed to direct solar radiation and heat sources (Table 6). Only the rooms of the upper floor (3 bedrooms, corridor and W.C.) were monitored during this period. During the calibration period the dwelling was not occupied. Internal gains from the equipment were minimal and the façade-roof window and shading elements of the upper floor were under the control of the research team (closed and open respectively).

The following three criteria were taken from these studies in the literature [66, 67] and were used in this work for the aforementioned case study model, to verify the agreement between the two datasets (simulated and measured) for each individual zone of the upper floor of the house:

a) Visual observation of general trends and time shifts (misalignment) between measurements and predictions.

b) Magnitude-fit metric defined as the absolute average temperature difference between the datasets. In the analysis, results less than 1.00°C (<1.00) were classed as "acceptable", although the actual acceptable ranges for calibration purposes would depend on the context of the comparison [67].

c) Shape-fit metric defined through the calculation of the Spearman's rank correlation coefficient and it highlights the level of correspondence (shape profile). In the analysis, results over 0.80 (>0.80) were classed as "acceptable" [67].

Although care was taken to ensure that model parameters were as accurate as possible to the real thermo-physical counterparts, there will still be uncertainty due to reasons related for example with uncertainty in thermo-physical properties of the envelope materials (poor craftsmanship and thermal bridges), glazing properties, infiltration and door openings, sensors accuracy and temperature stratification, erroneous selection of pressure coefficients and other reasons. Ad hoc calibration of the developed model was conducted to gauge the effect of assumptions on modelling parameters on the experimental response.

Figs. 5(a-c) present the monitored and simulated data series for three representative rooms of the upper floor. The comparison by visual observation shows adequate agreement, with maximum and minimum values occurring in a similar way and with the overall temperature fluctuations to follow a similar pattern. In addition, Table 7 presents the shape-fit and the magnitude-fit metrics for all the calibrated rooms. All rooms fulfill the requirements of the aforementioned metrics.

Table 6

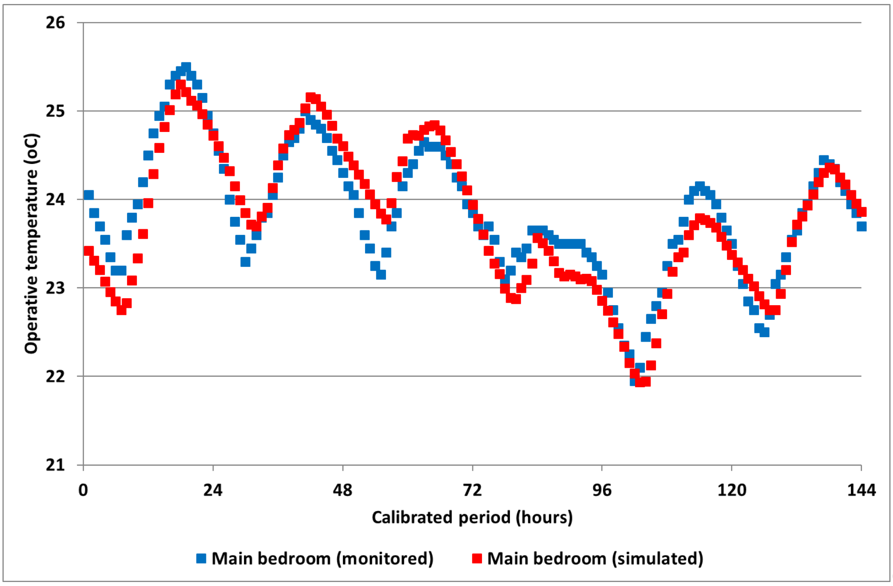
Range and accuracy levels of the sensors of the environmental parameters.

Metrics	Temperature (°C)	Relative humidity (%)	Carbon dioxide concentration (ppm)
Range	0÷50/-40÷65 (outdoor)	0÷100	0÷5000
Accuracy	±0.3	±3	±50 or 5%

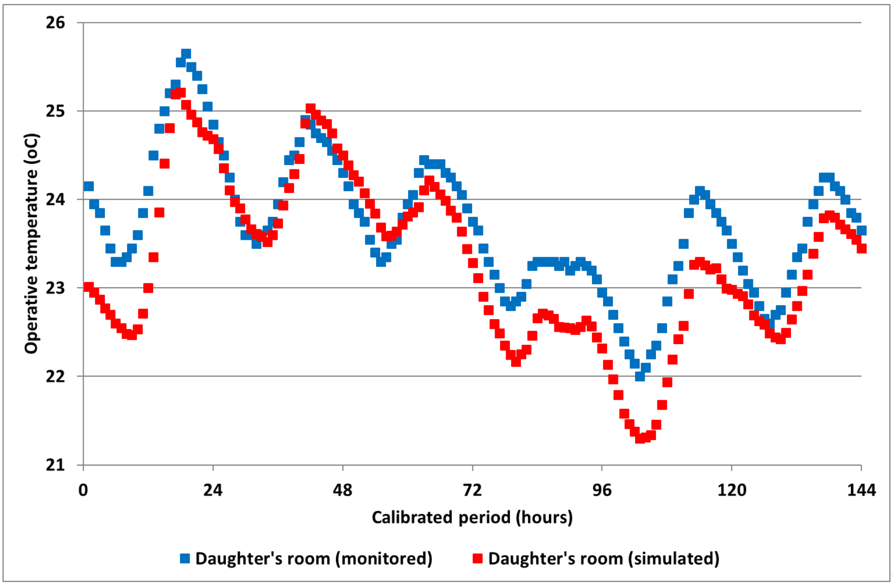
Table 7

Shape-fit and magnitude-fit metrics for all the simulated rooms of the upper floor for the total of the examined period.

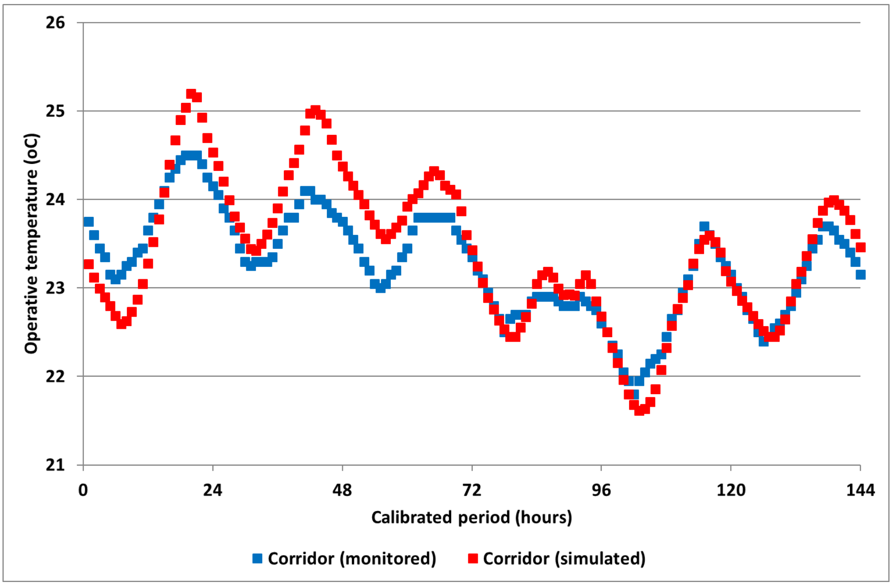
Metrics	Main bedroom	Son's room	Daughter's room	Corridor	W.C.
Spearman's coefficient	0.92	0.85	0.92	0.92	0.95
Absolute average temperature difference (°C)	0.3	0.6	0.5	0.3	0.6


26
25
24
23
22
21
Operative temperature (oC)
0
24
48
72
96
120
144
Calibrated period (hours)
Main bedroom (monitored)
Main bedroom (simulated)

(a)


26
25
24
23
22
21
Operative temperature (oC)
0
24
48
72
96
120
144
Calibrated period (hours)
Daughter's room (monitored)
Daughter's room (simulated)

(b)



(c)

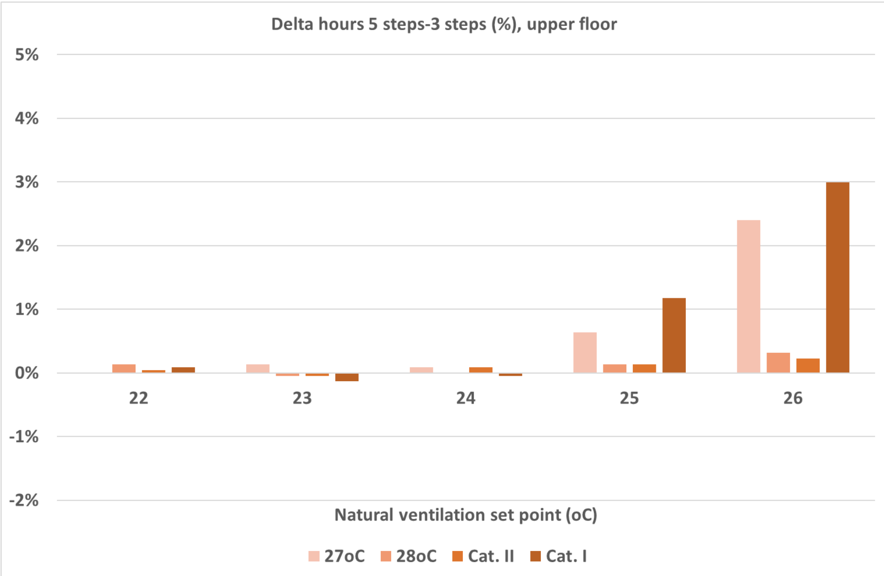
Fig. 5. Monitored and simulated indoor operative temperature (°C) series for the examined period and for different rooms of the upper floor (a: main bedroom, b: daughter's room and c: corridor).

3.2 Operational functions of window systems-Number of opening steps analysis

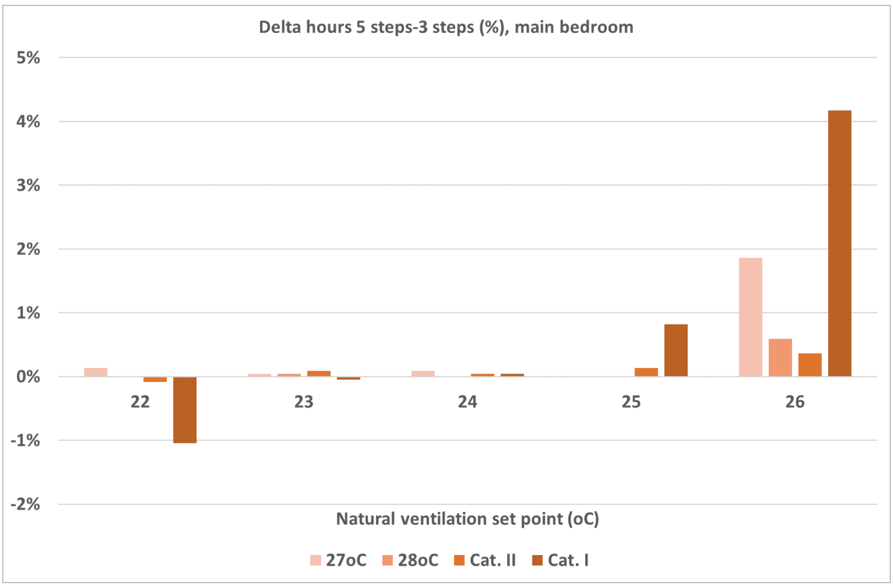
This section presents the comparison of the indoor thermal environments of the three-simulated bedrooms and the upper floor of the case study in total, based on two different thermal comfort and overheating assessment metrics (static and dynamic), four criteria (static: 27°C, 28°C and dynamic: Category II, Category I in Table 5) and for two different operational functions (control approaches) of the developed window system that have a different number of steps for the window actuator until the full opening of the window. The first control approach has three opening steps (25%/50%/100%; Fig. 2) and the second approach has five opening steps (10%/25%/50%/75%/100%; Fig. 2). The advantage of the 3-step approach is that the ventilative cooling strategy is more efficient, because the windows open faster (full opening in 3 time step intervals). The advantage of the 5-step is that the natural ventilation is more controllable in relation to the intense extreme outdoor conditions (wind speed) and could therefore in many cases eliminate the summer discomfort and the risk of overheating without causing considerable draft problems, high internal air velocities (internal damages) and considerable undercooling incidents. The time interval for the algorithm in both examined cases is similar, 30 minutes (Fig. 2). The developed algorithm is applied during all day for the whole examined period. The analysis covers different constant indoor natural ventilation cooling set points (22-26°C). Previous research has shown that ventilative cooling set points for similar automated window systems range inside this temperature band and are often around 24°C for these climatic conditions [28]. The parametric analysis will highlight which step-approach causes less discomfort and overheating risk for different examined set points.

Figs. 6 (a-d) present the percentage difference (delta; %) of the overheating risk and thermal discomfort for different indoor natural ventilation cooling set points, number of opening steps, metrics, criteria and rooms. The difference is positive for the majority of the set points, criteria and examined rooms of the upper floor. For all the assessed rooms and the floor in total, the differences are negligible (less than 0.5%) for low and medium natural ventilation cooling set points (22 to 24°C). For 22°C degrees, the adaptive approach (criterion Category I) and the south-oriented rooms, the difference is more profound (close to minus 1%). For higher set points (25 and 26°C), the differences are more profound (positive) for all rooms (especially criteria 27°C and Category I). The maximum value is resulted for the maximum set point of the parametric analysis, 26°C, for all the criteria and rooms. High trigger set points, close to the upper limits of the assessment criteria, result in lower performance of the ventilative cooling strategy. Higher internal temperatures occur when set points are set to high values and therefore the 3-step opening approach is suggested in these cases to provide ventilative cooling as fast as possible. The 3-step approach is suggested also for hotter climatic conditions with low ventilative cooling potential.

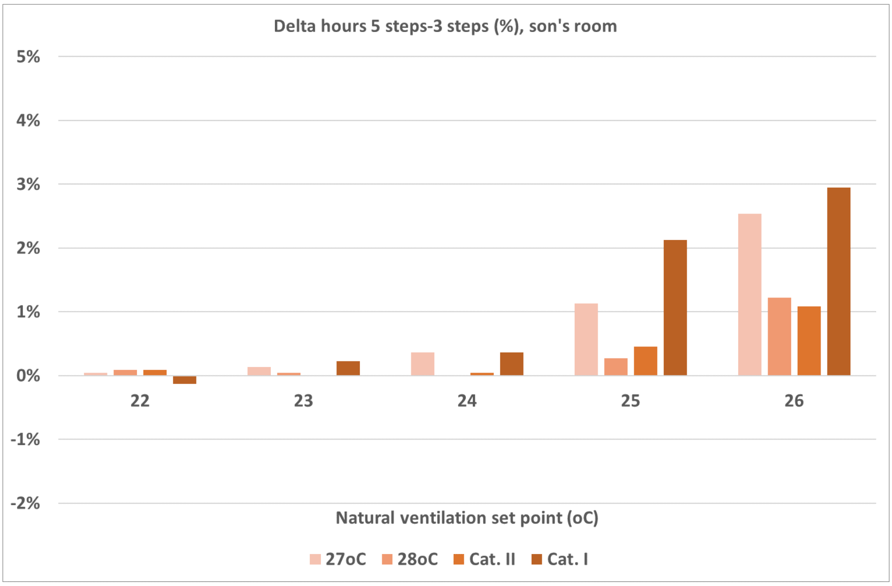
The results indicate that the effectiveness of the ventilative cooling strategy and the performance of the window system for these climatic conditions is not affected by the number of steps (3 or 5) for low and medium indoor natural ventilation cooling set points.


Delta hours 5 steps-3 steps (%), upper floor
5%
4%
3%
2%
1%
0%
-1%
-2%
22
23
24
25
26
Natural ventilation set point (oC)
27oC
28oC
Cat. II
Cat. I

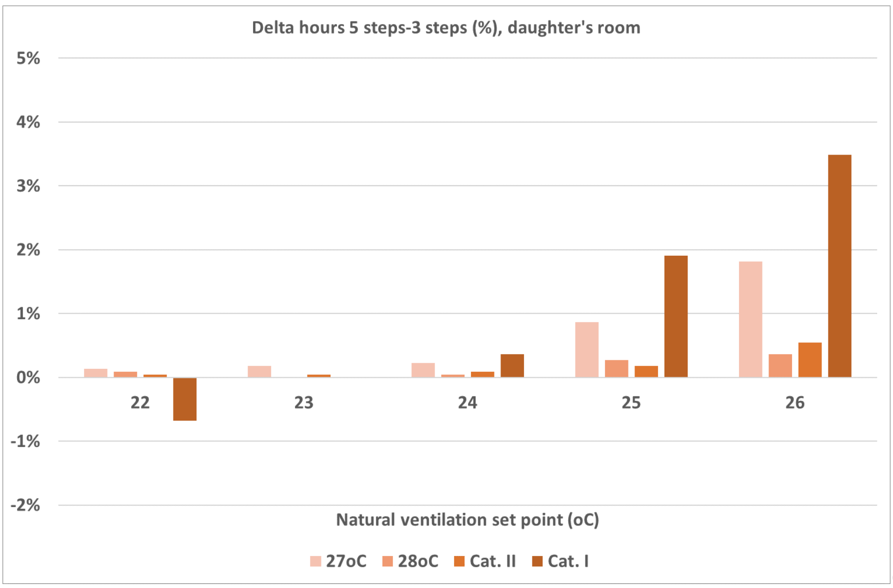
(a)


Delta hours 5 steps-3 steps (%), main bedroom
5%
4%
3%
2%
1%
0%
-1%
-2%
22
23
24
25
26
Natural ventilation set point (oC)
27oC
28oC
Cat. II
Cat. I

(b)



(c)



(d)

Fig. 6. Percentage difference-delta (5-step minus 3-step approach; %) of thermal discomfort and overheating risk for different rooms (a: upper floor on average, b: main bedroom, c: son’s room and d: daughter’s room) during the examined summer period and for different assessment metrics-criteria and indoor natural ventilation cooling set points.

3.3 Operational functions of window systems-Static versus dynamic indoor natural ventilation cooling *set points*

The determination of the optimum set point of a developed control algorithm is fundamental for the efficiency of the ventilative cooling method and the thermal optimization of the space. In this section, two different approaches have been examined for the determination of the optimum indoor natural ventilation cooling set point for actuating the window components. The first one is based on static discrete values of operative temperature and the second one on dynamically changing values based on the adaptive comfort temperature. The advantage of the former approach is that the occupant is aware about the set point values and has a physical feeling, understanding and responsibility about them. The advantage of the latter approach is that the system may calculate the dynamic set point with past outdoor temperature monitored values (Eqs. 1 and 2). This approach makes the window system more automated.

For this comparison between the two control approaches, all the rooms of the upper floor with window systems use the same approach (i.e. all static or all dynamic) and the same value (static) for the total of the examined period (summer 2016). The examined ranges of static set points are from 22 to 26^{o}C (1^{o}C intervals). The ranges of dynamic set points are from ±2^{o}C to comfort temperature (0.5^{o}C intervals). In addition, the algorithm follows the 5-step approach as described in Section 2.1 (Fig. 2). The time interval for the algorithm is the same in both examined cases (30 minutes). The algorithm is applied during the whole day.

Table 8 presents the ranking (high frequency to low frequency of thermal discomfort and risk) of the set points for both control approaches assessed by the two discomfort and overheating metrics and four criteria that were described in Sections 2.3. At the top of the Table there are the set points with the lowest thermal discomfort or risk. For all the rooms and floor in total, the static set points (22^{o}C and 23^{o}C) performs better than any dynamic set point for all the evaluating metrics and criteria (dynamic and static). Both northern and southern oriented rooms show similar results (Table 8).

It can be seen from Table 8 that the higher the set point value, the higher the thermal discomfort or risk. The static metrics have been optimized with the maximum hours of ventilative cooling. This has been accomplished by low indoor natural ventilation cooling set points (22^{o}C for this particular research). Dynamic criteria assess both overheating and undercooling incidents.

Categories I and II have been optimized in different set points (22°C and 23°C). Different case studies in different climates and with different internal and solar loads will result in different optimum set points.

Table 8

Ranking (lowest to highest frequency) of static and dynamic indoor natural ventilative cooling set points (°C), for three rooms (main bedroom, son's room and daughter's room) and upper floor (average), and four criteria (static: 27°C, 28°C and dynamic: Category II, Category I; $T_{cfrt.}$: stands for adaptive comfort temperature Eq. 1).

Discomfort	Upper floor				Main bedroom			
	27°C	28°C	Cat. II	Cat. I	27°C	28°C	Cat. II	Cat. I
Lowest frequency	22	22	22	23	22	22	22	23
	$T_{cfrt.}-2$	$T_{cfrt.}-2$	$T_{cfrt.}-2$	$T_{cfrt.}-1$	$T_{cfrt.}-2$	$T_{cfrt.}-2$	23	$T_{cfrt.}-1.5$
	23	23	23	24	23	23	$T_{cfrt.}-2$	24
	$T_{cfrt.}-1.5$	$T_{cfrt.}-1.5$	$T_{cfrt.}-1.5$	$T_{cfrt.}-1.5$	$T_{cfrt.}-1.5$	$T_{cfrt.}-1.5$	$T_{cfrt.}-1.5$	$T_{cfrt.}-2$
	24	$T_{cfrt.}-1$	$T_{cfrt.}-1$	$T_{cfrt.}-0.5$	$T_{cfrt.}-1$	$T_{cfrt.}-1$	$T_{cfrt.}-1$	22
	$T_{cfrt.}-1$	24	24	$T_{cfrt.}-2$	24	24	24	$T_{cfrt.}-1$
	$T_{cfrt.}-0.5$	$T_{cfrt.}-0.5$	$T_{cfrt.}-0.5$	22	$T_{cfrt.}-0.5$	25	$T_{cfrt.}-0.5$	$T_{cfrt.}-0.5$
	25	$T_{cfrt.}$	$T_{cfrt.}$	$T_{cfrt.}$	25	$T_{cfrt.}-0.5$	$T_{cfrt.}$	$T_{cfrt.}$
	$T_{cfrt.}$	25	25	25	$T_{cfrt.}$	$T_{cfrt.}$	25	25
	$T_{cfrt.}+0.5$	26	$T_{cfrt.}+0.5$	$T_{cfrt.}+0.5$	$T_{cfrt.}+0.5$	$T_{cfrt.}+0.5$	$T_{cfrt.}+0.5$	$T_{cfrt.}+0.5$
	26	$T_{cfrt.}+0.5$	$T_{cfrt.}+1$	$T_{cfrt.}+1$	26	26	26	$T_{cfrt.}+1$
	$T_{cfrt.}+1$	$T_{cfrt.}+1$	26	26	$T_{cfrt.}+1$	$T_{cfrt.}+1$	$T_{cfrt.}+1$	$T_{cfrt.}+1.5$
	$T_{cfrt.}+1.5$	$T_{cfrt.}+1.5$	$T_{cfrt.}+1.5$	$T_{cfrt.}+1.5$	$T_{cfrt.}+1.5$	$T_{cfrt.}+1.5$	$T_{cfrt.}+1.5$	26
Highest frequency	$T_{cfrt.}+2$	$T_{cfrt.}+2$	$T_{cfrt.}+2$	$T_{cfrt.}+2$	$T_{cfrt.}+2$	$T_{cfrt.}+2$	$T_{cfrt.}+2$	$T_{cfrt.}+2$

Discomfort	Son's room				Daughter's room			
	27°C	28°C	Cat. II	Cat. I	27°C	28°C	Cat. II	Cat. I
Lowest frequency	22	22	22	23	22	22	22	23

	23	$T_{cfrt.}-2$	$T_{cfrt.}-2$	$T_{cfrt.}-1.5$	$T_{cfrt.}-2$	$T_{cfrt.}-2$	$T_{cfrt.}-2$	$T_{cfrt.}-1.5$
	$T_{cfrt.}-2$	23	23	$T_{cfrt.}-1$	23	23	23	$T_{cfrt.}-2$
	$T_{cfrt.}-1.5$	$T_{cfrt.}-1.5$	$T_{cfrt.}-1.5$	24	$T_{cfrt.}-1.5$	$T_{cfrt.}-1.5$	$T_{cfrt.}-1.5$	$T_{cfrt.}-1$
	24	$T_{cfrt.}-1$	24	$T_{cfrt.}-2$	24	24	$T_{cfrt.}-1$	24
	$T_{cfrt.}-1$	24	$T_{cfrt.}-1$	22	$T_{cfrt.}-1$	$T_{cfrt.}-1$	24	22
	$T_{cfrt.}-0.5$	$T_{cfrt.}-0.5$	$T_{cfrt.}-0.5$	$T_{cfrt.}-0.5$	$T_{cfrt.}-0.5$	$T_{cfrt.}-0.5$	$T_{cfrt.}-0.5$	$T_{cfrt.}-0.5$
	25	25	$T_{cfrt.}$	$T_{cfrt.}$	25	25	$T_{cfrt.}$	$T_{cfrt.}$
	$T_{cfrt.}$	$T_{cfrt.}$	25	25	$T_{cfrt.}$	$T_{cfrt.}$	25	25
	$T_{cfrt.}+0.5$	$T_{cfrt.}+0.5$	$T_{cfrt.}+0.5$	$T_{cfrt.}+0.5$	$T_{cfrt.}+0.5$	$T_{cfrt.}+0.5$	$T_{cfrt.}+0.5$	$T_{cfrt.}+0.5$
	$T_{cfrt.}+1$	26	$T_{cfrt.}+1$	$T_{cfrt.}+1$	$T_{cfrt.}+1$	26	$T_{cfrt.}+1$	$T_{cfrt.}+1$
	26	$T_{cfrt.}+1$	26	26	26	$T_{cfrt.}+1$	26	$T_{cfrt.}+1.5$
	$T_{cfrt.}+1.5$	$T_{cfrt.}+1.5$	$T_{cfrt.}+1.5$	$T_{cfrt.}+1.5$	$T_{cfrt.}+1.5$	$T_{cfrt.}+1.5$	$T_{cfrt.}+1.5$	26
Highest frequency	$T_{cfrt.}+2$	$T_{cfrt.}+2$	$T_{cfrt.}+2$	$T_{cfrt.}+2$	$T_{cfrt.}+2$	$T_{cfrt.}+2$	$T_{cfrt.}+2$	$T_{cfrt.}+2$

4. Conclusions

Passive and hybrid ventilation and ventilative cooling methods, techniques, strategies and technologies may significantly decrease the environmental impact of residences and create healthy and comfortable indoor spaces. One of the challenges with assessing and demonstrating the benefits of automated controlled ventilative cooling strategies is the lack of well documented, mature and validated BPS tools which may replicate and represent precisely the complexity of air-movement physics and the control of the automated systems.

This research works presents a representation and simulation of a developed ventilative cooling algorithm on coupled BPS environments through a well-defined proposed framework and workflow. Under this framework that the use of ESP-r and BCVTV tools facilitate, the simulation of any other developed window system or ventilative cooling concept for different climatic conditions and building types is possible.

An analytical parametric analysis of the developed window system in roof window configurations of a typical single-family house in Denmark was conducted and it was found that the effectiveness and performance of the ventilative cooling strategy for these climatic conditions was not affected by the number of opening steps (3 or 5) for low and medium natural indoor ventilation cooling set points (22-24°C). In addition, for all the examined rooms, the static set points perform better (best results with 22°C and 23°C) than the dynamic for all the evaluating metrics and criteria (dynamic and static) that were included in this study.

Further investigation of the developed window system and algorithm in other building types and climatic conditions is suggested for future work. The description of the ventilative cooling heuristic algorithm of the window system can be used as a baseline for further development of window systems for residential cases in temperate climates or in more complicated architectural layouts and building types. The examination of different dynamic-based ventilative cooling set points resulting from future climatic conditions could also be investigated in the future. In addition, the proposed window system outputs of this research could be used as supporting material for installed window systems in these climatic conditions. However, the outputs are sensitive to climatic conditions and building types, and therefore additional modelling by following a similar methodology as in this study is recommended.

5. Acknowledgement

The authors are presently contributing to the ongoing work for investigating and maturing ventilative cooling as an attractive and energy-efficient solution to avoid overheating of both new and renovated buildings within the IEA EBC Annex 62: Ventilative Cooling. The research was developed within the framework of the project "Ventilative cooling in energy renovated residences" of Aalborg University, Denmark, and was supported by EUDP (Energy Technology Development and Demonstration Program) and VELUX A/S, DOVISTA A/S and VISILITY ApS (Grant number 64013-0544/2014-2017). Part of this work has been developed with ARENS, under a Commonwealth Grant Agreement with the Australian Government-Department of Industry and Science.

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Appendix V

Article 5

Psomas T, Heiselberg P, Duer K, Bjørn E. Control strategies for ventilative cooling of overheated houses. Federation of European Heating, Ventilation and Air-conditioning Associations: Proceedings of 12th REHVA World Congress, Aalborg, Denmark. Aalborg University; 2016.

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Control Strategies for Ventilative Cooling of Overheated Houses

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Abstract

Buildings constructed before 1979 in Denmark are responsible for 75% of the total energy consumption of the sector. However, many post-occupancy comfort studies of energy renovated dwellings have documented elevated temperatures not only during the summer period but also during the transition months. Ventilative cooling can be an energy-efficient solution to avoid overheating in energy renovated residences.

The aim of the research is to investigate the ability of a representative manual window use and different automated window control strategies in order to eliminate overheating under different opening positions, wind conditions and discharge coefficients. The study will also include examination of the ability of mechanical ventilation and shading systems regarding the overheating occurrence. The objectives are fulfilled through the simulation and analysis of a real representative single-family house from the 1970s. The case study is renovated deeply and high-efficient (nZEB) creating two different scenarios.

Mechanical ventilation system and manual control of the openings for both renovation scenarios cannot sufficiently eliminate the overheating risk indoors. The discharge coefficient of the windows, the presence of the wind and the opening position of the windows are critical parameters of the effectiveness of the ventilative cooling strategies. The fully all-day automated control strategy presents the best performance among the three strategies of the automated control (parallel use, automated during the occupied period and fully automated). In most of the cases of the parametric analysis the high-efficient renovation scenario presents lower values of overheating risk compared to the deep renovation scenario.

Residential building; renovation; passive measure; building automation

1. Introduction

The building sector is responsible for more than 30% of the energy use [1] and carbon emissions in the European Union [2]. In Denmark the building stock accounts for about 40% of the total final energy use [3]. Buildings constructed before the 1980s are responsible for 75% of the total energy use of the sector [4]. During the 1960s and 1970s, approximately 440,000 (more than the one third in total) single family dwellings were built in Denmark [5]. The majority of them are identical in terms of size, construction systems and materials. These houses were erected without or with the first limited energy regulations. In many cases these buildings have not yet undergone deep or high-efficient energy renovations [6]. In 2012 a broad majority in the Danish parliament agreed on the transition to fossil independency until 2050, by increasing the ambitions regarding energy savings in general [7]. The energy-efficient Danish regulations (BR10 and BR2015/2020) brought important changes in the design process mainly concentrated on an increase of the airtightness and insulation levels of the building [8]. However, in many post-occupancy comfort studies of new or energy renovated dwellings elevated temperatures have been documented not only during the summer period but also during the transition months [9, 10]. As cooling becomes a need not only in the summer period, but also during the transition months, the possibilities of utilizing the free cooling potential of low temperature outdoor air increases considerably. Orme et al. [11] documented that the most important factors causing overheating and discomfort conditions in well insulated houses are the solar radiation and the limited ventilation rates.

Ventilation is already present in most residential buildings through mechanical and/or natural systems and can both remove excess heat gains as well as increase air velocities and thereby widen the thermal comfort range [12]. For home owners cooling is an unknown challenge that they have not experienced before. They do not know how to efficiently reduce the overheating problem indoors and their behavior might instead actually increase it.

The aim of the research is to highlight the problem of overheating in energy renovated single-family houses in Denmark and to investigate the ability of a representative "typical" manual window use and different automated window control strategies in order to eliminate risk under different opening positions (percentages), wind conditions and window discharge coefficients (parametric analysis). The study will also include examination of the ability of mechanical ventilation and shading systems regarding the overheating occurrence. The objectives are fulfilled through the investigation of the comfort conditions of a representative dwelling from the 1970s. The case study is retrofitted deeply and high-efficient (nearly zero energy building-nZEB) creating two different renovation scenarios.

2. Methodology

2.1 Case Study

The case study is a representative one-story single-family house (116.2m2, net floor area) from the 1970s (1973-1978) as extracted from "Typology Approach for Building Stock Energy Assessment" project. The case study is reference by definition, as far as the geometry, size, energy performance, materials, window area and structure of the Danish residences of this period. The case study is a typical heavy-weight construction [13-Fig. 1]. Table 1 presents the thermal characteristics of the dwelling.

The case study is renovated deeply and high-efficient (nZEB) creating two different scenarios (Table 1). In the first step the dwelling is renovated deeply, according to the energy regulations for existing buildings [8]. In the second step the case study is renovated to reach very efficient energy goals (BR2020). Three typical roof windows with south orientation have been used as part of the renovation process. The openings cover the 10%/35%/10%/0% of the external walls (north/south/east/west).

Fig. 1 Case study

Table 1. Thermal characteristics of the case study for different renovation phases

Renovation	U_{wall} (W/m²K)	U_{roof} (W/m²K)	U_{floor} (W/m²K)	U_{window}, g (W/m²K),-	n_{50} (ach/h)
Base case	0.45	0.45	0.35	2.7, 0.76	5.0
Deep	0.20	0.15	0.12	1.65, 0.7	1.6
nZEB	0.10	0.15	0.12	1.2, 0.6	0.8

The analyses were conducted with the use of highly sophisticated building performance simulation tool DesignBuilder version 4.2. The renovation cases were simulated as free floating buildings (transition and summer season), without any mechanical cooling systems. The weather file used in the simulations was well documented, free accessible Energy Plus file (.epw) with hourly data (Fig. 2). The occupancy and internal gain profiles [13] reflect a typical 5-member working family (Table 2).

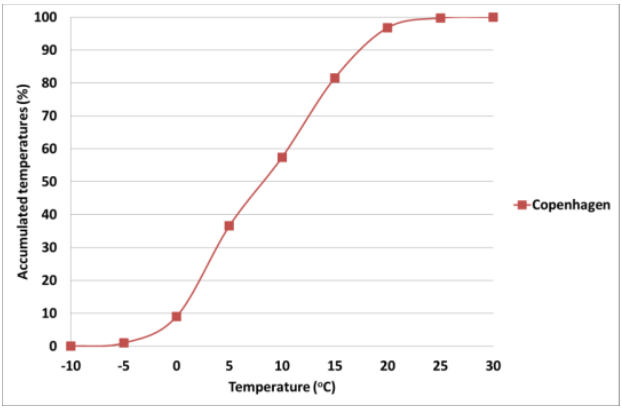

Fig. 2 Accumulated temperature (°C), weather file of Copenhagen, Denmark

Table 2. Occupancy profile

	Monday-Thursday	Friday	Weekend
Occupied	00:00-08:00/ 16:00-24:00	00:00-08:00/ 14:00-24:00	fully
Non-occupied	08:00-16:00	08:00-14:00	-

The overheating occurrence is assessed by the method "percentage outside of the range" of EN 15251:2007 standard [12]. The index measures the percentage of the occupied hours with operative temperatures higher than the upper and lower bound of the adaptive comfort temperature. In our cases for renovated residences, Category II is used. The method is used for the assessment of overheating in "free-running" buildings (no mechanical cooling) and especially residential houses where the options (e.g. access to operable windows) and possibilities of thermal adaptation of the occupants are plenty [12]. The overheating incidents were observed from middle of April to middle of October. No undercooling incidents were observed for the examined period.

2.2 Control Strategies and Parametric Analysis

This research has examined five different ventilative control strategies. The first examined strategy is through the mechanical ventilation system. The air change rate is set to 0.5 ach during all day, covering the minimum indoor air quality requirements (no heat recovery). When the outdoor temperature is colder than the indoor mechanical ventilation offers refreshing air, which decreases the overheating problem indoors. Occupants of dwellings do not use both mechanical ventilation systems and openings as a result of the strict suggestions (oriented to the heating period) of the installers.

Several behavioral models have been developed in the last years aiming to predict occupant-controlled window opening in naturally ventilated or conditioned buildings [14]. These models have been created mainly from data of office buildings and their use is extended to domestic environments. The models created for residential buildings are limited and case study or climate related. Residents of single-family buildings used to open the windows, mainly for indoor air quality reasons or as a result of a "typical" practice, in specific times during the day (morning, after work-cooking time, before sleep). This daily pattern is considered in this paper as "typical" representative manual use (Table 3). The manual opening is applied to all the windows of the case study, independently of the outdoor environmental conditions during the examined period.

Table 3. Typical manual use of the windows

	Opening hours
Morning	07:00-08:00
Afternoon	16:00-18:00
Night	23:00-24:00

For the first two control strategies, overheating was calculated also with the application of different shading systems (drapery, internal/mid-pane/external blinds with high reflectivity) for intercomparison reasons [13]. The shading systems were applied only during the non-occupied period (Table 2) for visibility reasons.

Finally, the last three examined control strategies are related with automated control of the openings:

- Automated control during the non-occupied hours and at night and manual control (Table 3),
- Fully automated (occupied hours),
- Fully automated (all-day).

The automated control for ventilative cooling is based mainly on indoor temperature setpoints and outdoor temperatures. The windows open when the outdoor temperature is lower than the indoor (always over 12.5^{o}C) and the indoor temperature over a benchmark.

Ventilative cooling is vulnerable to constraints and limitations when applied in real cases (e.g. security, outdoor weather conditions, noise, children or animal safety, insects and others). It is important that the control strategies are also examined under different ventilation parameters which affect the performance and effectiveness on the dwelling. This analysis covers mainly three parameters: the discharge coefficient settings, the wind effect and the opening of the windows (Table 4). The indoor natural ventilation temperature set point was set to 22^{o}C to avoid undercooling incidents. This value is the result of desk sensitivity analysis (not presented in this paper) and suggested for the Danish building stock. No undercooling risk is observed for any of the control strategies, parametric analysis and renovation scenarios. The parametric analysis has been conducted for both renovation scenarios.

Table 4. Different values of the analysis

Discharge coefficient (C_d)	0.45/0.65
Wind effect	wind/no wind
Window opening (%)	10/50

3. Results

The comfort assessments, without the use of any shading systems and ventilative cooling through mechanical ventilation systems, show extreme values of overheating (33.4% and 35.8% respectively-Fig. 3). Similar results are presented also for manual control of openings (23.6% and 25.6% respectively-Fig. 4).

The use of different shading systems significantly decreases the overheating occurrences for both control strategies and renovation scenarios (Figs. 3 and 4). For the most effective shading measure (high reflectivity external blinds) the decrease of the overheating risk for the two renovation scenarios is 73% and 70% respectively (mechanical ventilation) and 75% and 77% respectively (manual control). For manual control of the windows and the use of the most effective shading system the overheating risk is approaching the acceptable benchmark of the regulations (EN 15251:2007). Always for these strategies the more efficient scenario presents higher overheating risk.

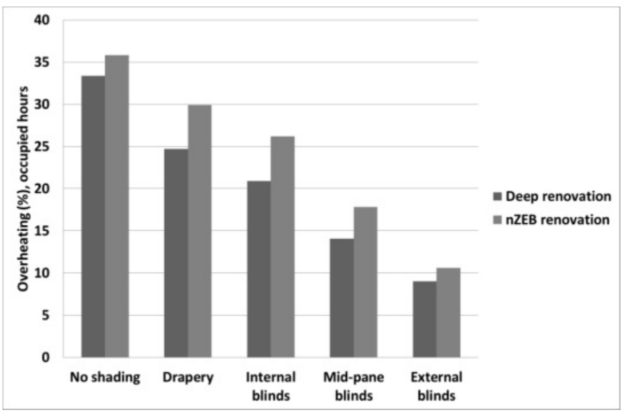

Fig. 3 Overheating assessment (%) without or different shading systems and ventilative cooling through mechanical systems (two renovation scenarios)

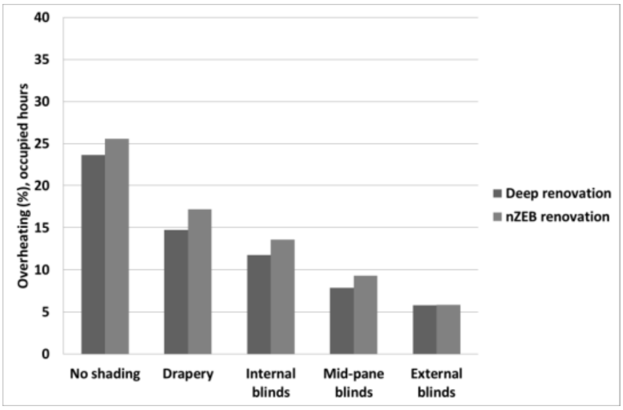

Fig. 4 Overheating assessment (%) without or different shading systems and manual control of the windows (wind effect, discharge coefficient: 0.65 and window opening: 10%, two renovation scenarios)

Manual control for both renovation scenarios and all the examined parameters cannot sufficiently eliminate the overheating risk (over the benchmarks). The increase of the discharge coefficient of the windows, the presence of the wind effect and the increase of the window opening significantly decrease the overheating incidents for both scenarios and all the examined control strategies (manual, mixed and automated). The lowest values are 8.7% and 7.8% for deep and nZEB renovation scenarios respectively. The highest values are 35.5% and 37.2% respectively for low discharge coefficients, low window opening and without wind (urban conditions). In general, the highly open window (50%) is more effective in high discharge coefficients. Window opening percentage seems to be the most crucial parameter for the ventilative cooling effectiveness indoors. In general the increase of the window opening from 10% to 50% result a decrease of the overheating 81.3% on average (79.2% for deep renovation and 83.4% for high-efficient renovation). In addition, for high values of window opening (50%) the nZEB renovation scenario presents lower risk compared to the deep renovation scenario.

Table 5 presents comfort assessments for different mixed or automated ventilative cooling control strategies, wind conditions, window opening percentages and discharge coefficients for different renovation scenarios. The mixed control strategy (manual and automated) is the worst control strategy among the three. For two cases (deep renovation) and for one case (nZEB renovation) of the parametric analysis, the overheating occurrence is over the benchmark of the regulations (5%, EN 15251:2007). The all-day automated control presents the lowest values of overheating occurrence. All the results of the parametric analysis present overheating risk under 5%. For three cases the overheating risk is minimal (zero).

Table 5. Overheating (%) for different mixed and automated control strategies and parameters (two renovation scenarios)

wind effect-C_d-opening	Automated (non-occupied, night) and manual control	Automated control (occupied hours)	Automated control (all-day)
Deep renovation			
wind-0.65-10%	2.4	1.5	0.8
wind-0.65-50%	0.5	0.1	0.0
wind-0.45-10%	3.4	2.7	1.5
wind-0.45-50%	0.6	0.3	0.1
no wind-0.65-10%	6.5	4.7	2.8
no wind-0.65-50%	1.4	0.8	0.4
no wind-0.45-10%	10.1	7.9	5.0
no wind-0.45-50%	1.8	1.0	0.6
nZEB renovation			
wind-0.65-10%	1.4	0.9	0.3
wind-0.65-50%	0.2	0.1	0.0
wind-0.45-10%	2.5	1.6	0.7
wind-0.45-50%	0.3	0.1	0.0
no wind-0.65-10%	4.6	3.3	1.8
no wind-0.65-50%	0.8	0.3	0.2
no wind-0.45-10%	8.1	5.9	3.3
no wind-0.45-50%	1.2	0.5	0.2

On average the effectiveness of the automated control strategies is approximately 95% (compared with mechanical ventilation systems) and almost 90% (compared with manual control of the windows) in overheating terms. The comparison of the results between the manual control and the mixed control highlights the importance of the night ventilative cooling to the design without overheating problems, especially for temperate climates. The forced manual control, in many cases, worsens the comfort conditions indoors because the user allows hot air (e.g. during afternoon) to enter the space (air quality reasons). The mixed control strategy may not be sufficient to compensate overheating issues in residences, which are subjected to climate change effects, even in Denmark in the next decades.

The differences on the results between the most effective automated control strategies are low. For Denmark ventilative cooling may be an effective solution also during the non-occupied hours in the morning. On the other hand, the fully automated all-day control strategy raises serious concern as far as the security of the dwelling because the windows open when the occupant is not at home. Special concern as far as the configuration of these openings has to be taken into account. Contemporary security systems or old fashion metal bars might solve the security issues in case studies where the effectiveness of the control strategy is more profound.

For all the cases of the parametric analysis of the automated control strategies the nZEB renovation scenario presents lower values of overheating occurrence compared to the deep renovation scenario. Ventilative cooling measures controlled by automated systems are more effective to more efficient houses.

4. Conclusions

Mechanical ventilation system and manual control of the openings for both renovation scenarios cannot sufficiently eliminate the overheating risk indoors. For manual control of the windows and the use of the most effective shading system the overheating risk is approaching the acceptable benchmark of the regulations. The automated control of the window openings significantly eliminates the overheating problem indoors for both renovation scenarios in all of the cases. The all-day automated control presents the lowest values of overheating occurrence. The discharge coefficient of the windows, the presence of the wind and the opening position of the windows are critical parameters of the effectiveness of the ventilative cooling strategies. Ventilative cooling controlled by automated systems are more effective to more efficient houses.

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The authors are presently contributing to the ongoing work with investigating and maturing ventilative cooling as an energy-efficient solution to avoid overheating of buildings, within the IEA EBC Annex 62: Ventilative Cooling.

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